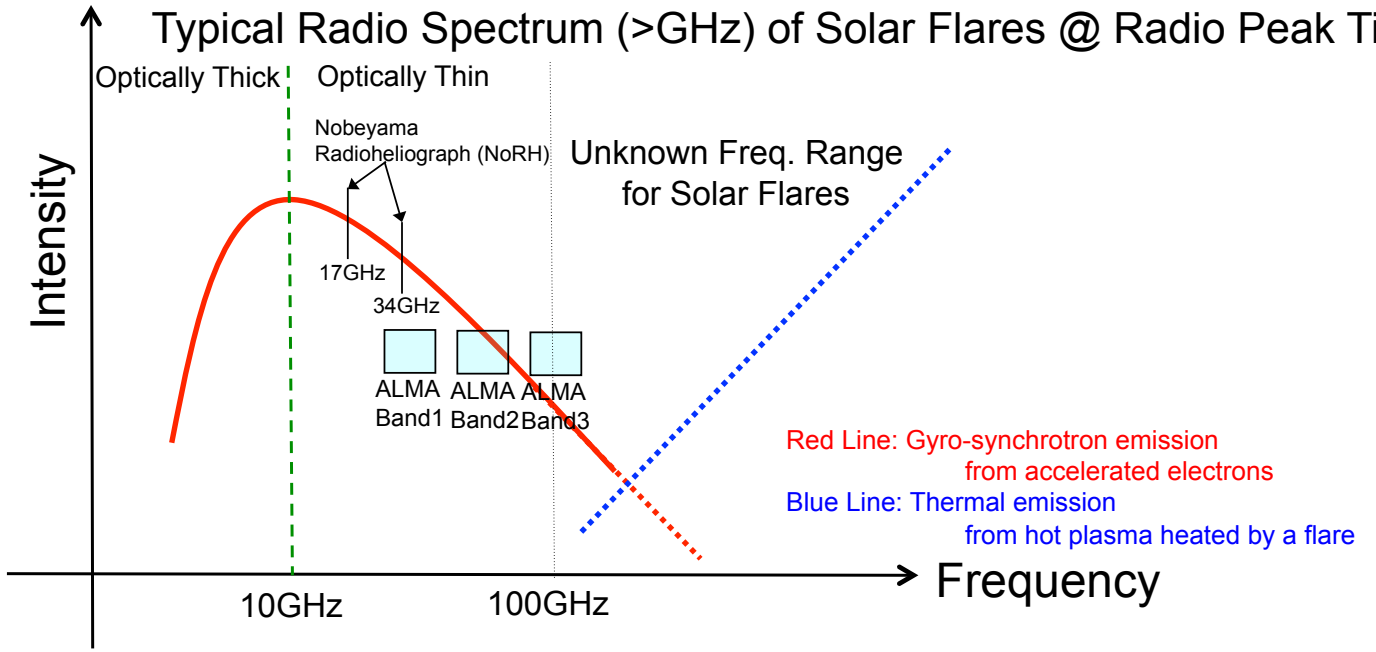
# リムフレアにおける
# 非熱的粒子観測

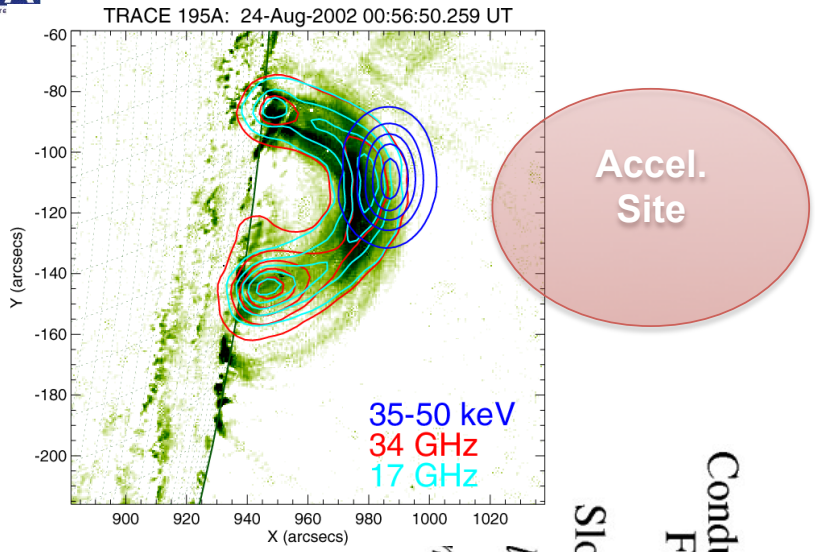
今田晋亮　（名大STE）

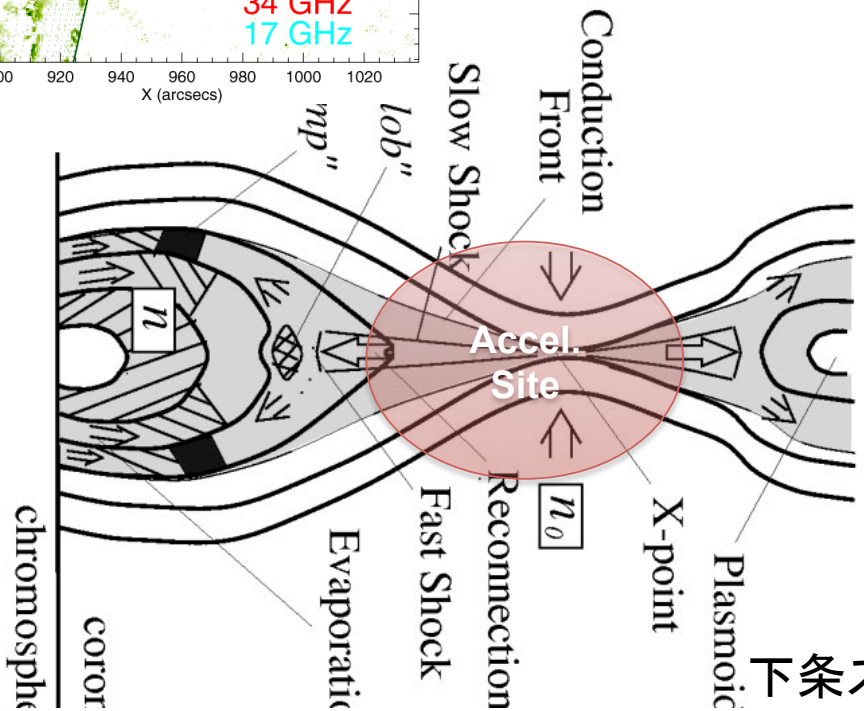
# フレアからの電波放射(>GHz)

- >100GHzの周波数は、太陽物理にとって未開の地。
  - ALMA Band 3 (~100GHz)あたりは、数MeV電子からのジャイロシンクロトロン放射による電波。
  - 最近、数百GHzの観測結果が出てきているが、全て空間分解されていないデータ。



# ALMAでここからの信号が受かれば…



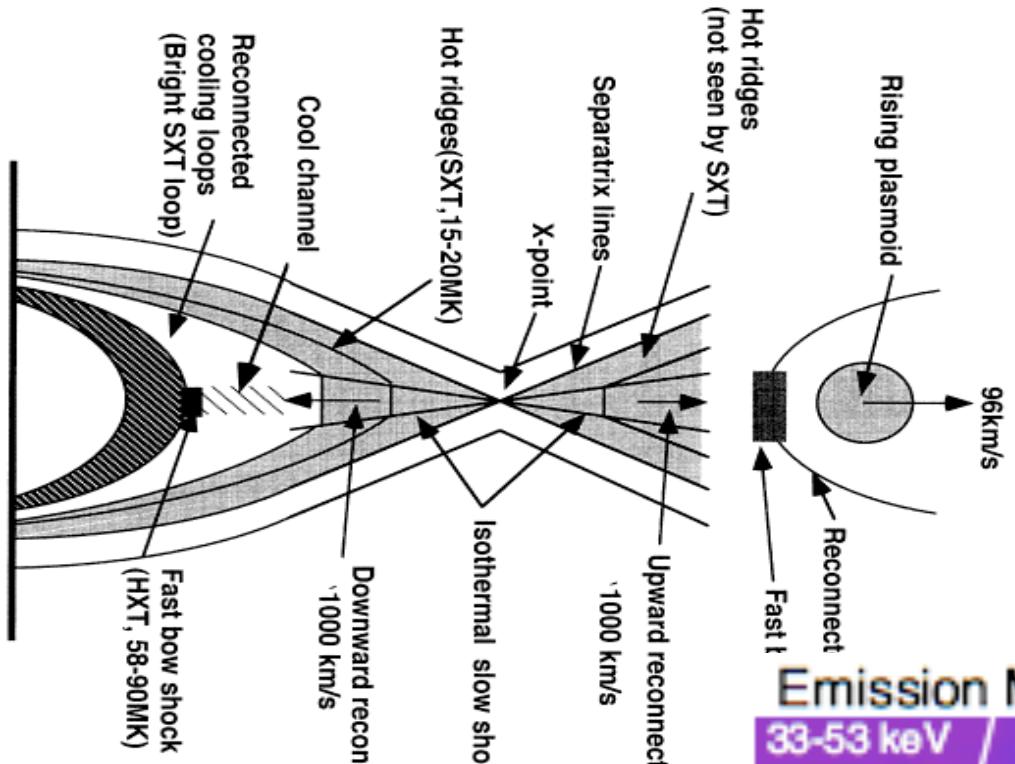

- 加速サイトにいる電子からの放射が見たい。
- ダイナミックレンジの問題。
  - NoRH: ~300
  - HXT/Yohkoh: ~10
  - RHESSI:~10
  - ALMA: > 1000

下条スライド@太陽研究会'11　より

# 今日の話

- 加速領域について、及び加速過程
- 加速領域の熱的なプラズマの振る舞い
- 地球磁気圏プラズマとの相違・共通性

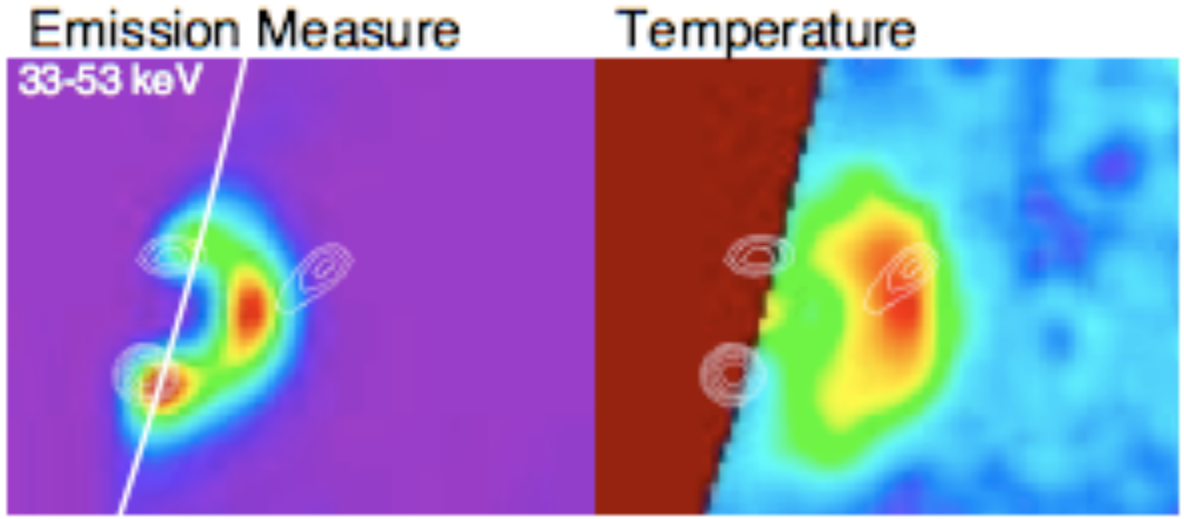
# Standard model for Solar Flare





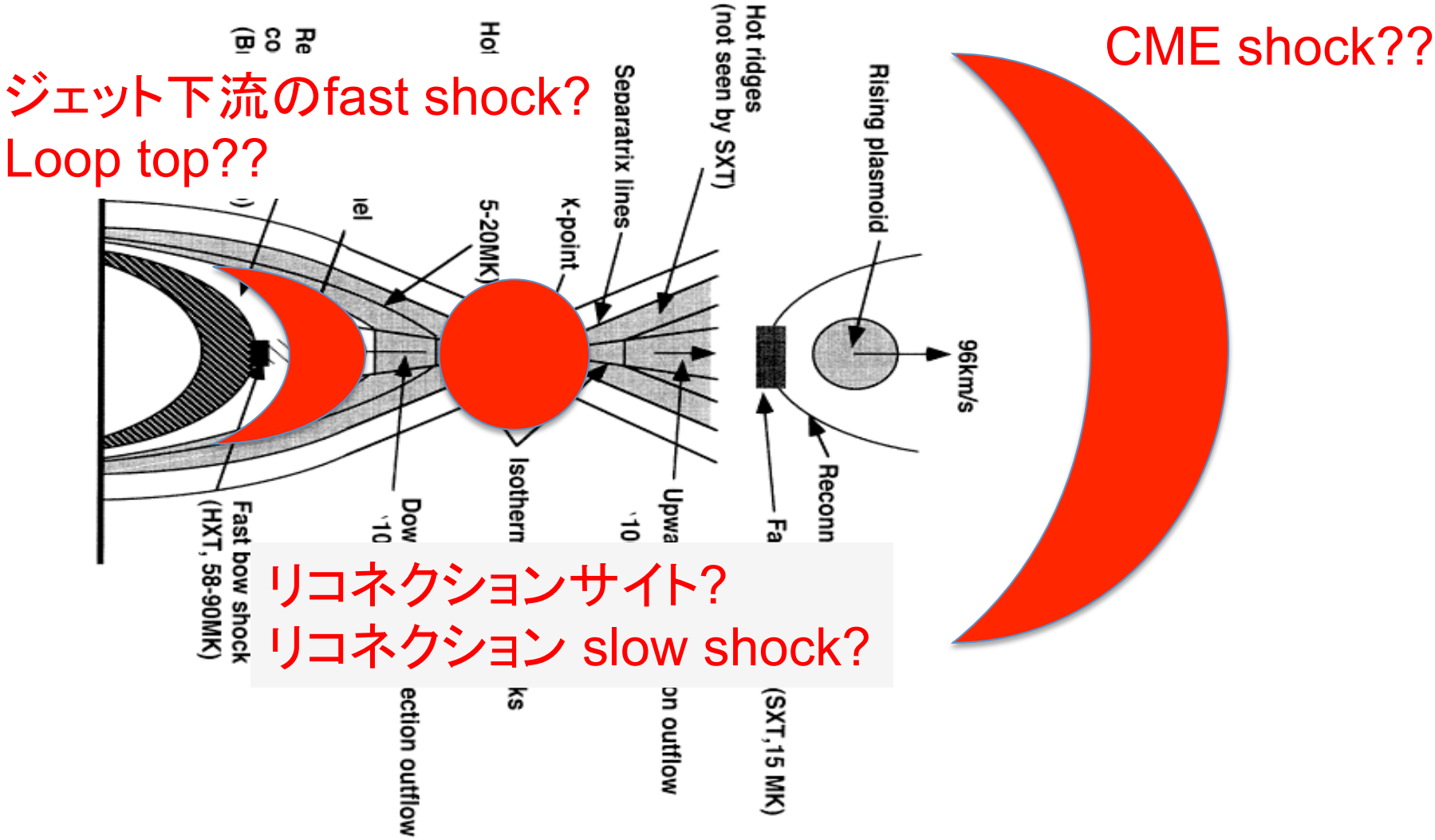


リコネクションサイト?
リコネクション slow shock?
ジェット下流のfast shock?
Loop top??
CME shock??

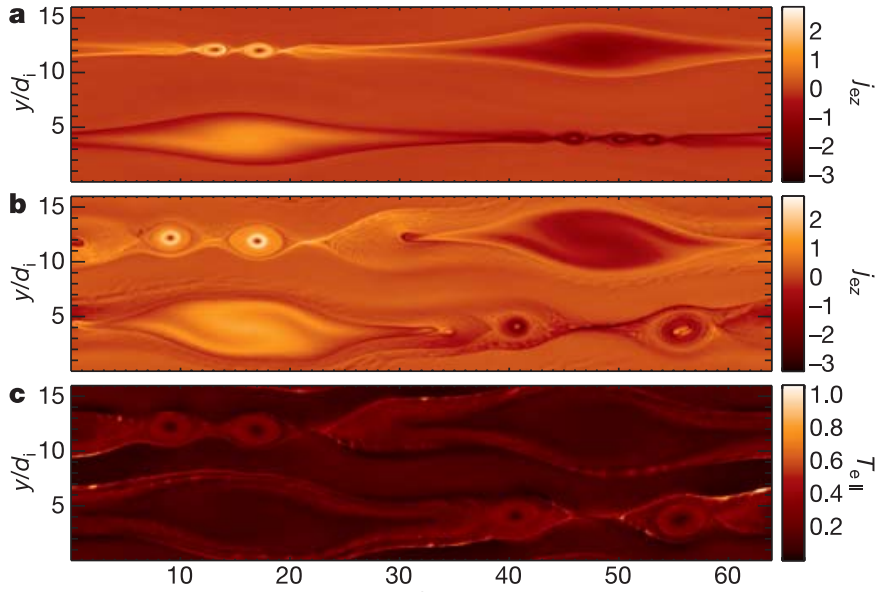



**Tsuneta et al., 1996**

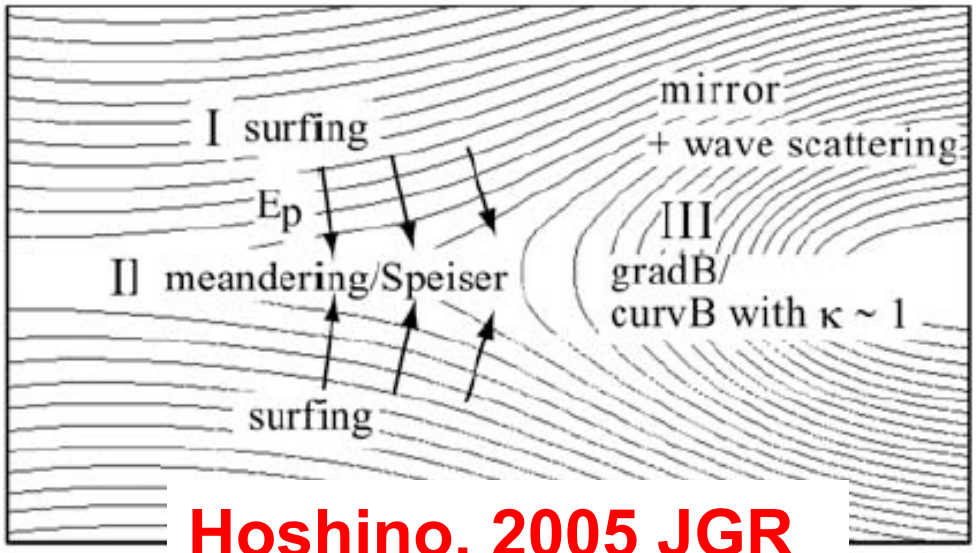
# どこで～MeV電子が見える？



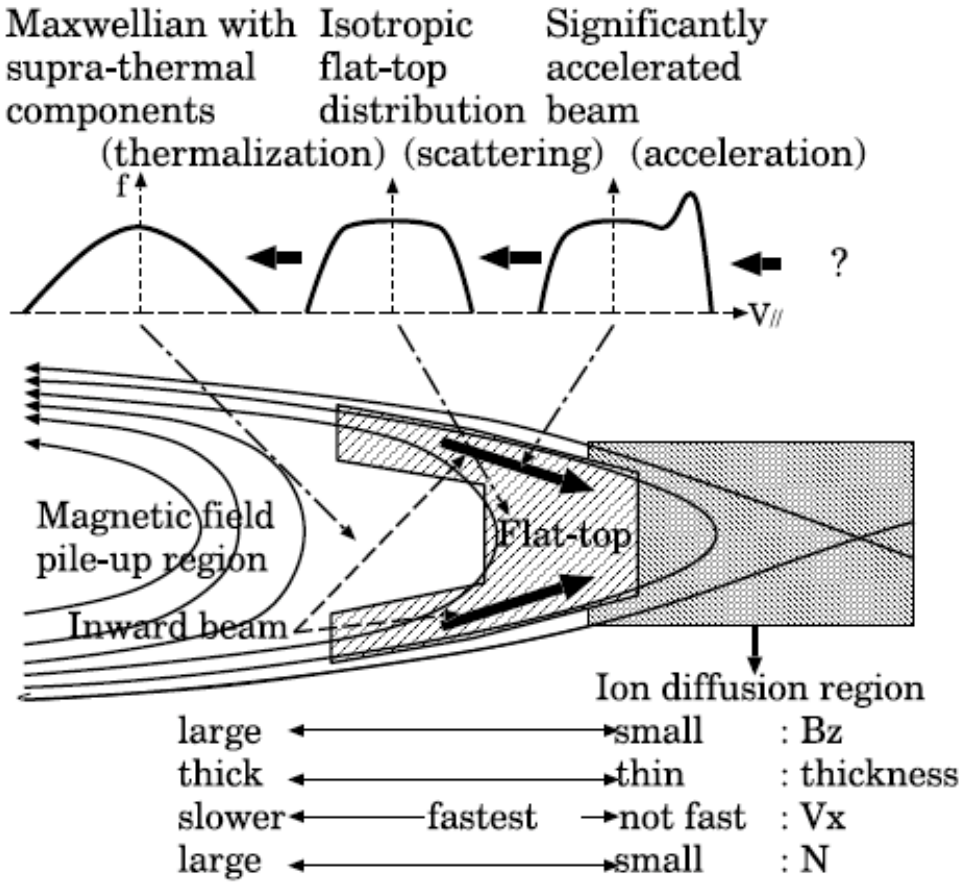
# リコネクション周りの加速




Drake+, 2006 Nature



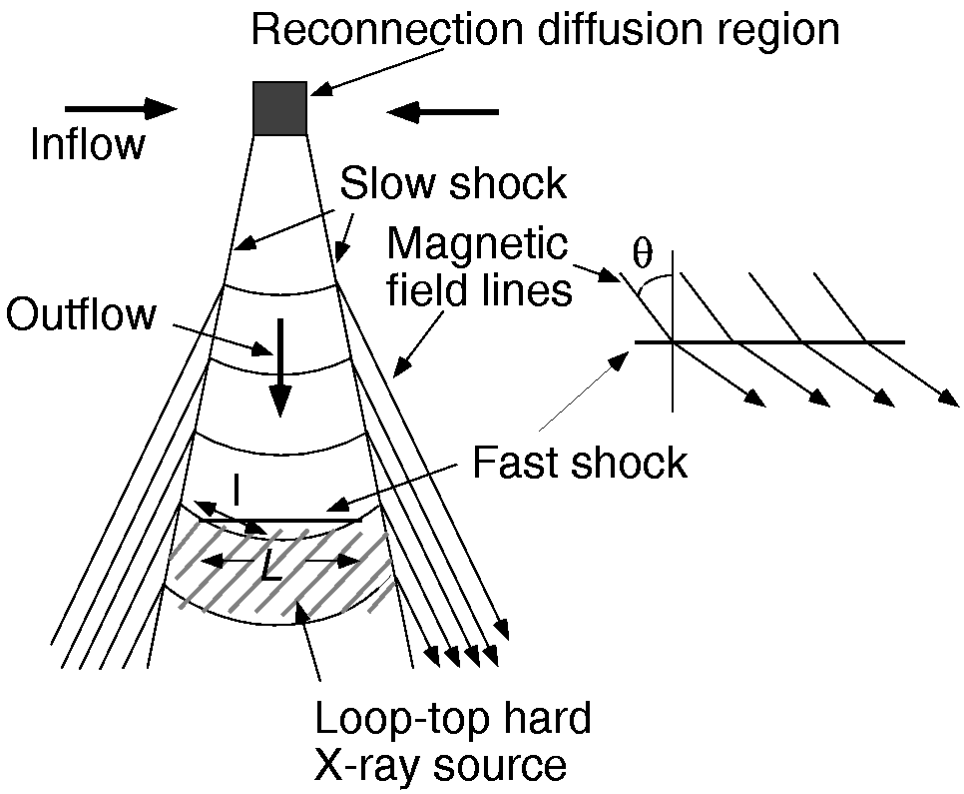

Hoshino, 2005 JGR




Asano+, 2008 JGR

# Loop Top 加速

Fermi acc.

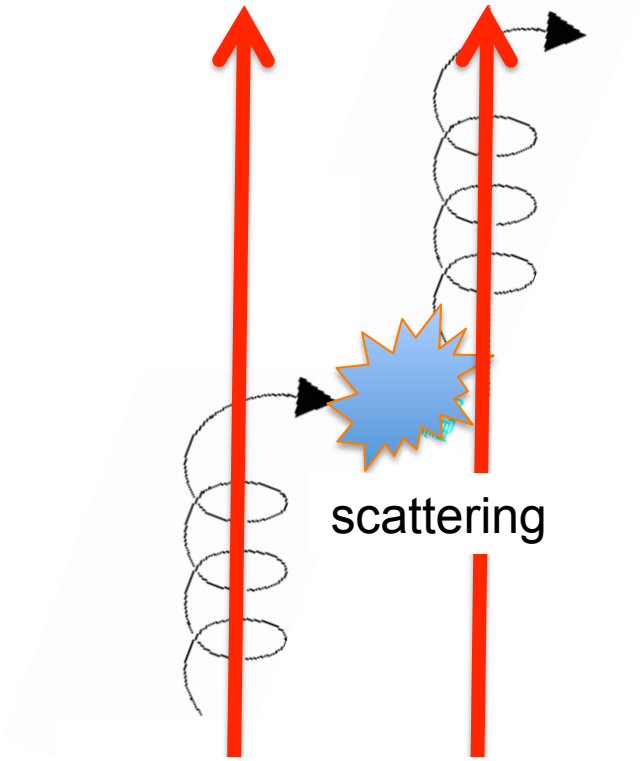



**Tsuneta, 1998 ApJ**

**Imada PhD thesis**

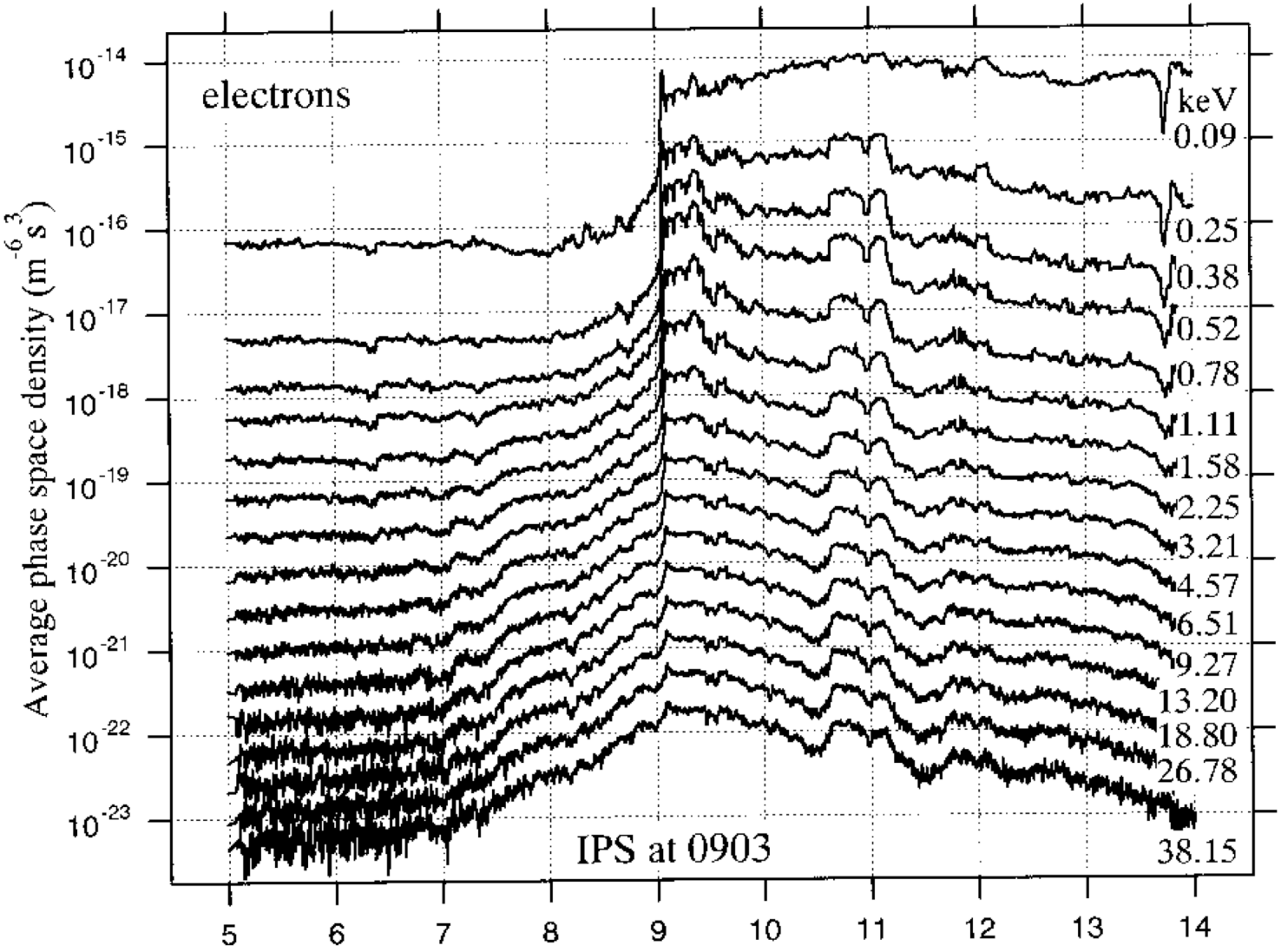
Cross field diffusion

Without energy changing



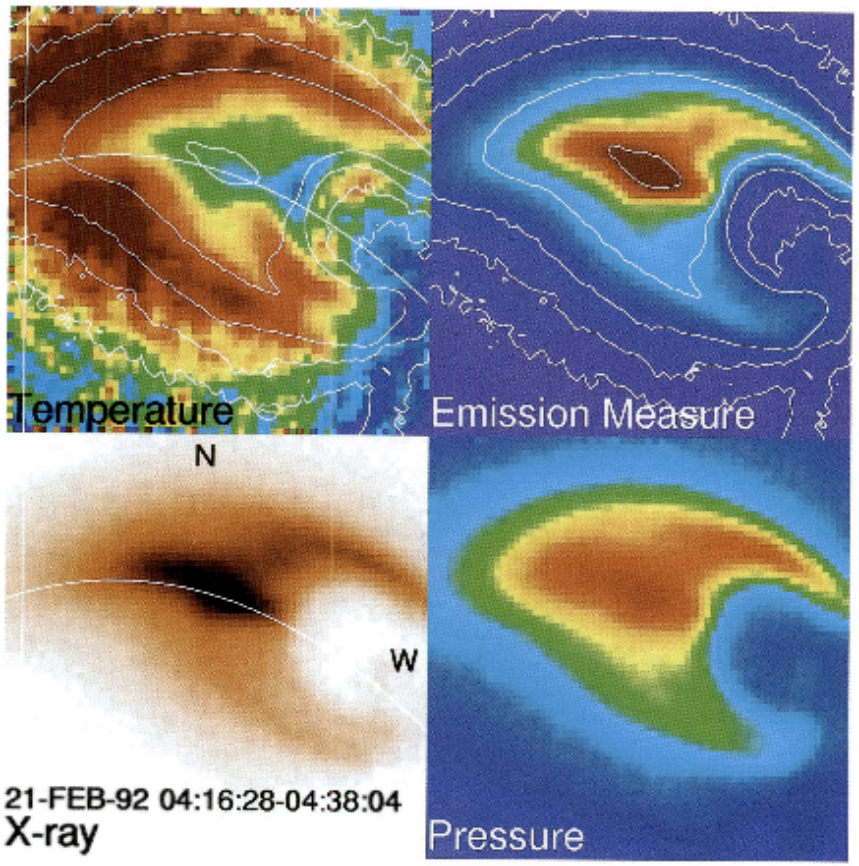

1. grad B -> break adiabatic invariant
2. Electric field -> max energy

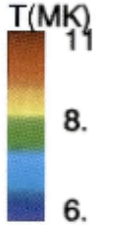
# Shock acceleration

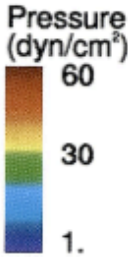


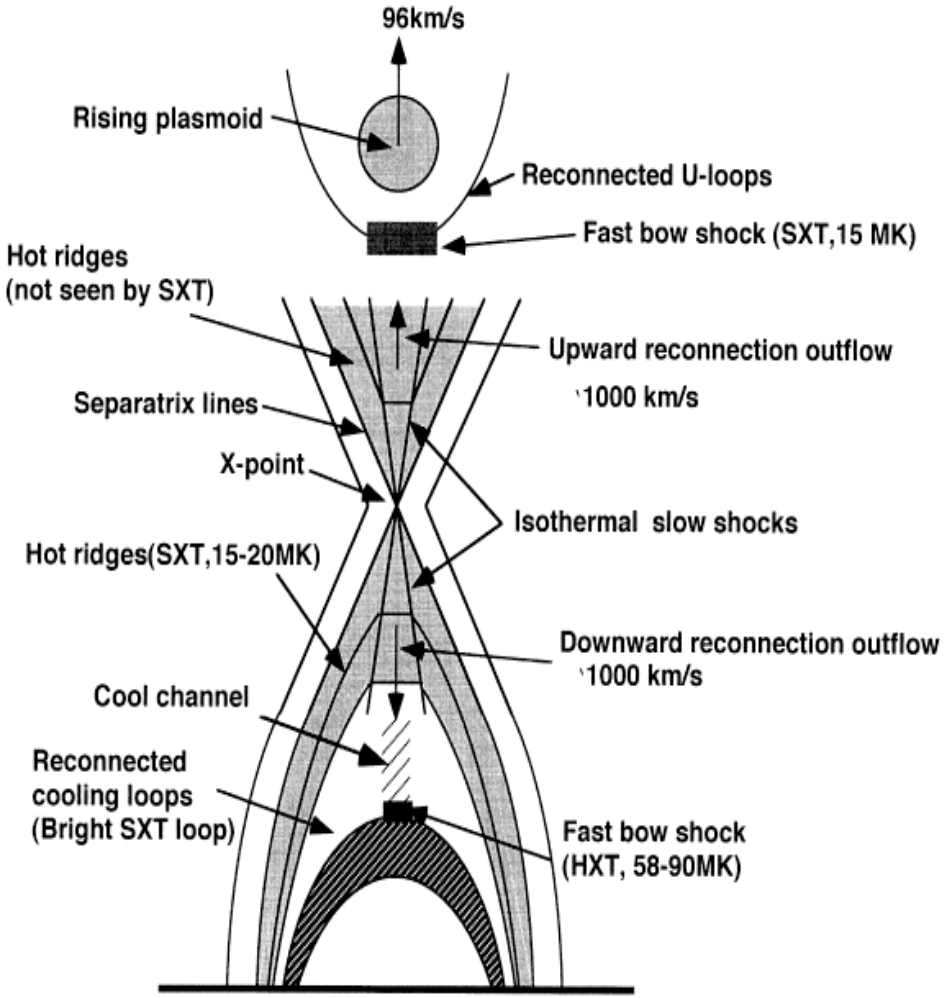

Shimada+ ApSS 1999

# Flare Standard Model



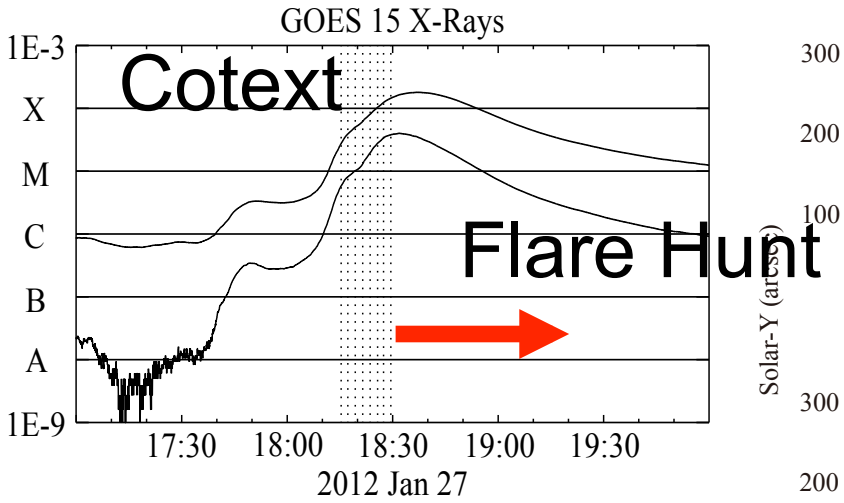

**Tsuneta et al., 1996**

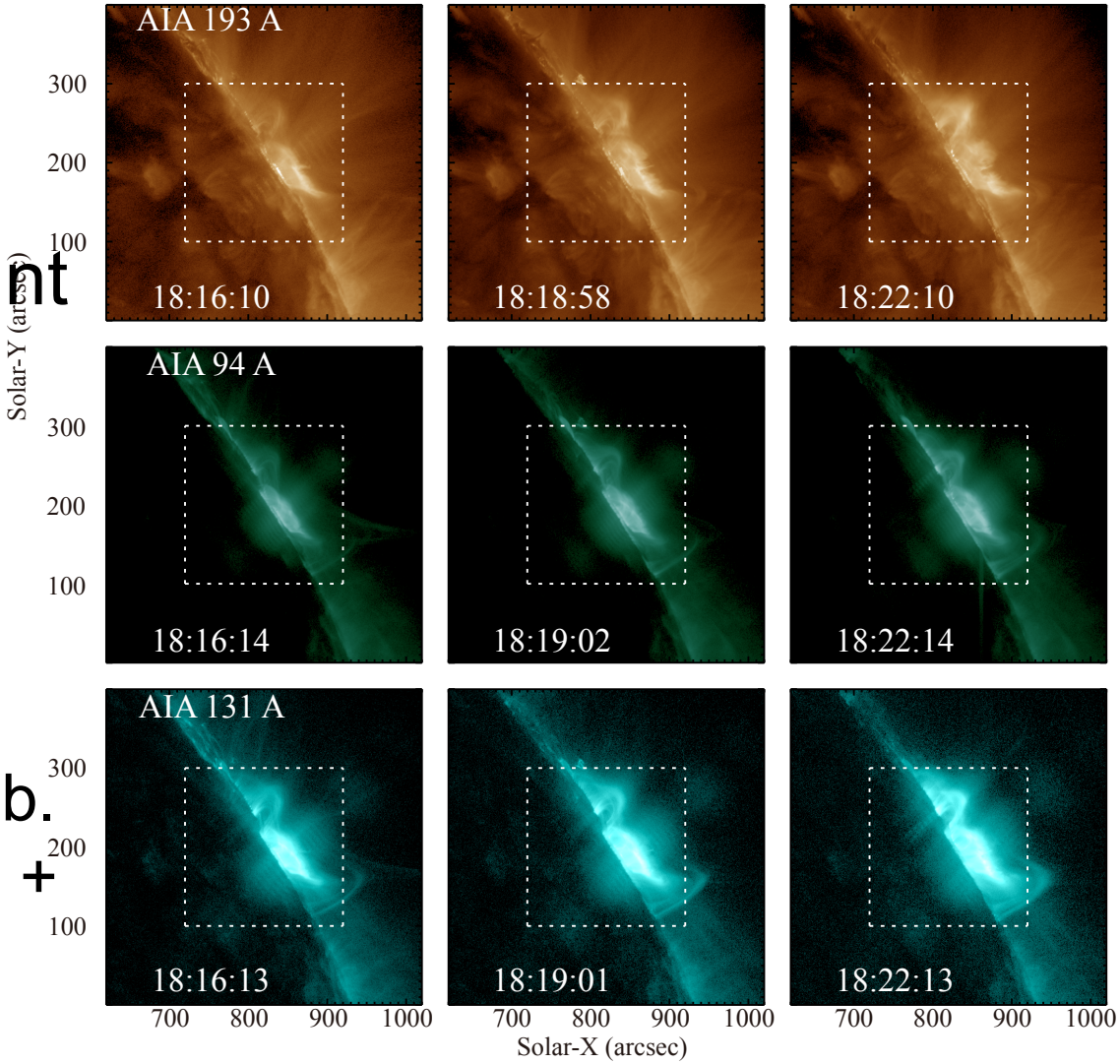
Flare standard model predict Hot (>20MK)

Alfvenic plasma flow (~1000km/s) above the flare loop.

Spectroscopic observation (EIS) is crucial for understanding.

# 2012 Jan 27 (18:15) GOES X1.7

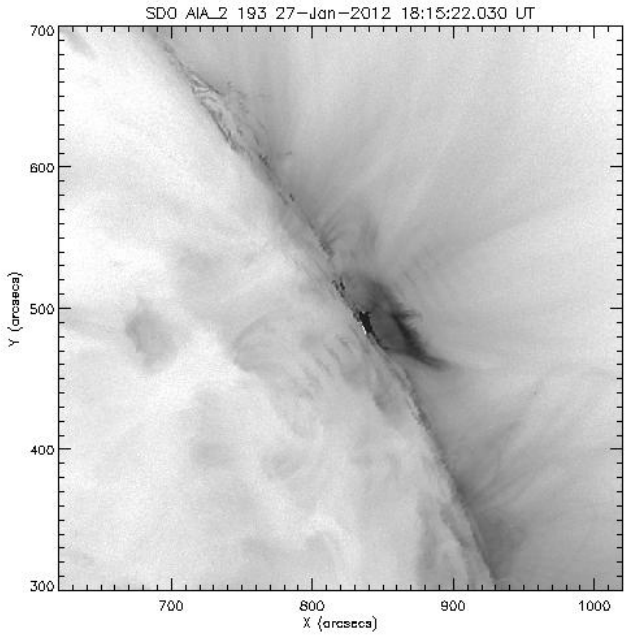


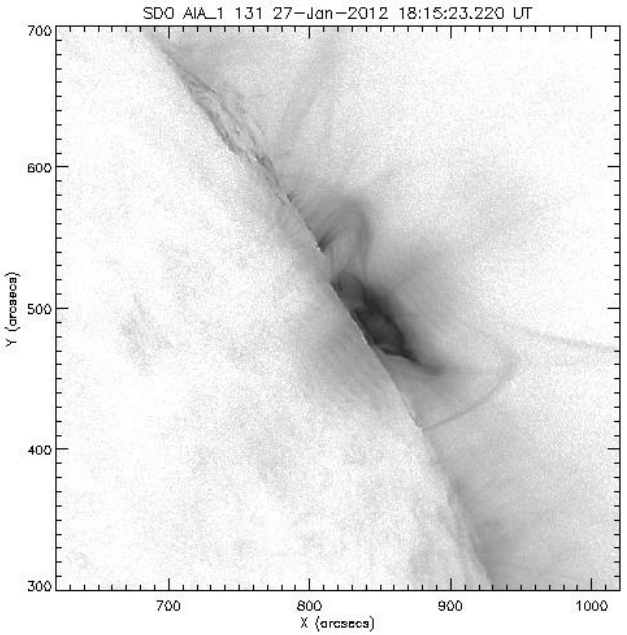

First Limb X-class flare observed by Hinode.
Flare occurred near East limb.
EIS performed Context scan + Flare hunting.

# AIA Observation of X-class Flare

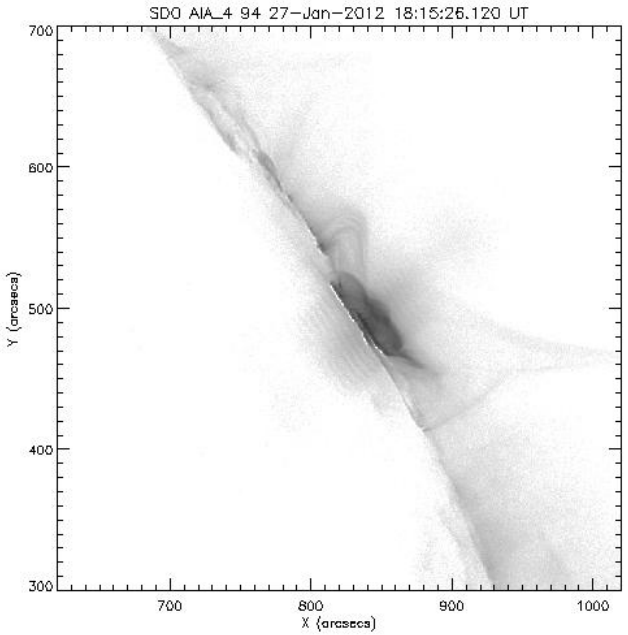
193 A (1.5 or 15MK)




131 A (10MK)

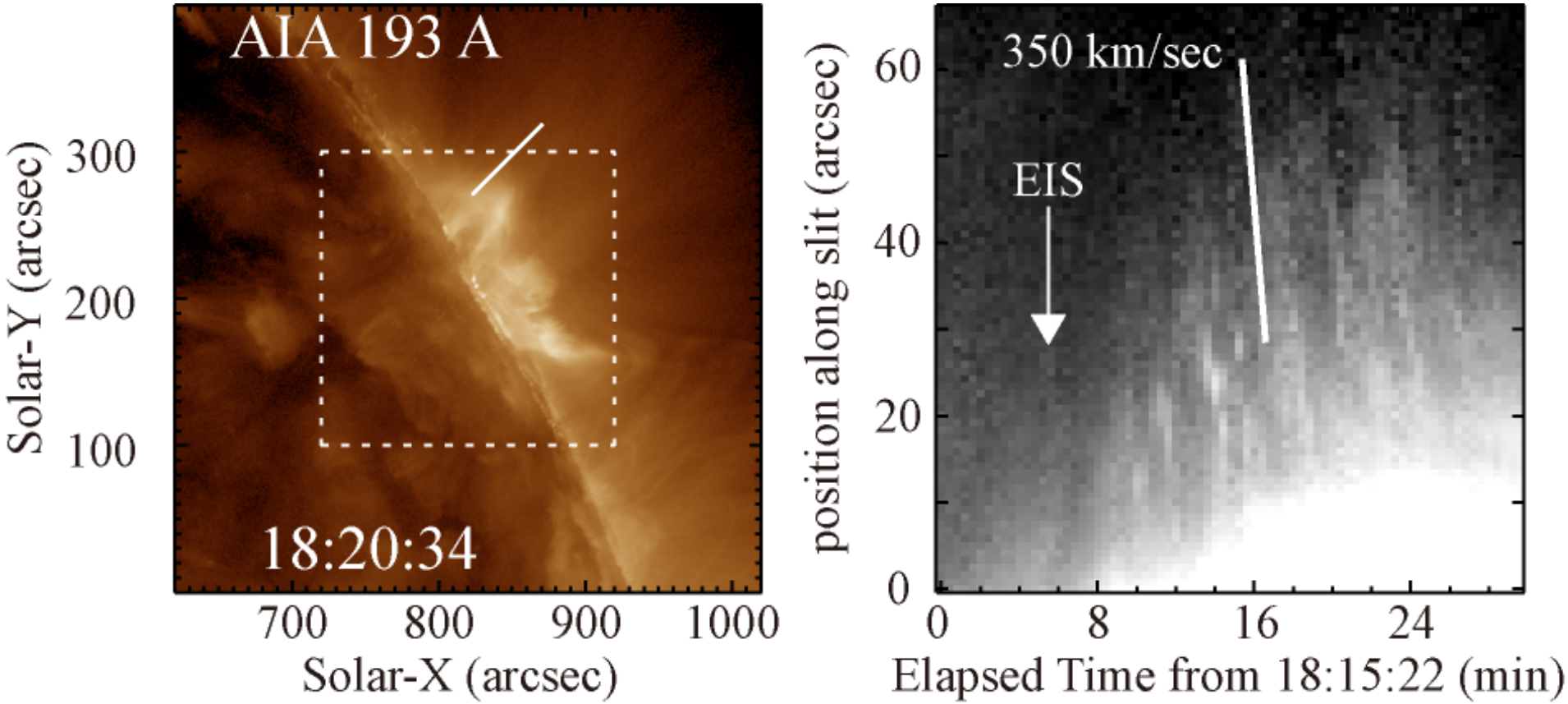



94 A (8Mk)




193 A images are very similar to those 131A.
Thus, the photons in 193 A images should be from FeXXIV during the event.
We confirmed 193 A image represent FeXXIV during this event from EIS obs.
Fast Supra-Arcade Downflows and Downflowing Loops were observed.

# Supra-Arcade Downflowing Loops

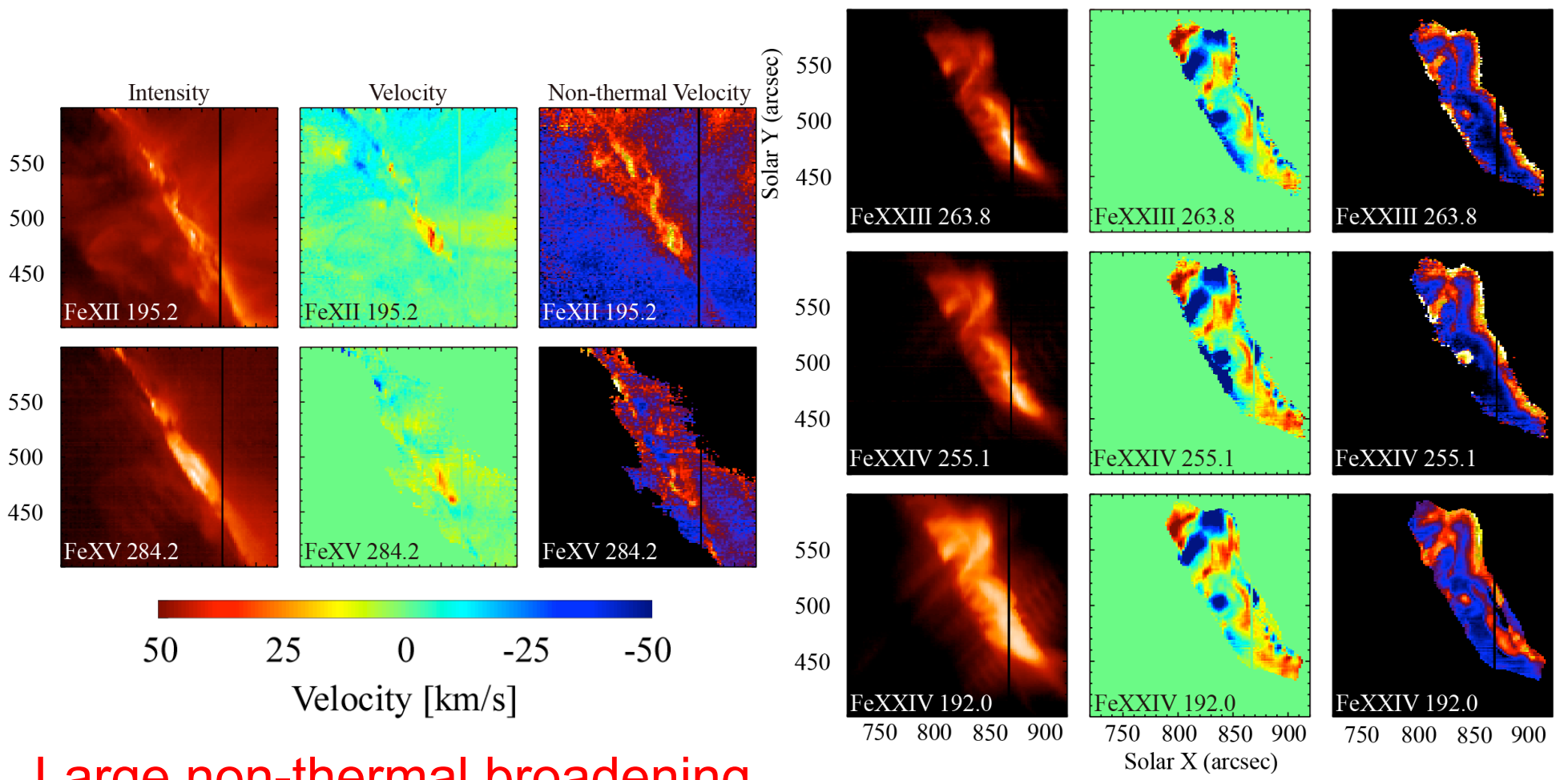



SADLS speed is roughly 350km/s.

SADLS temperature ~30MK by ratio between 193/131A DN (>10).

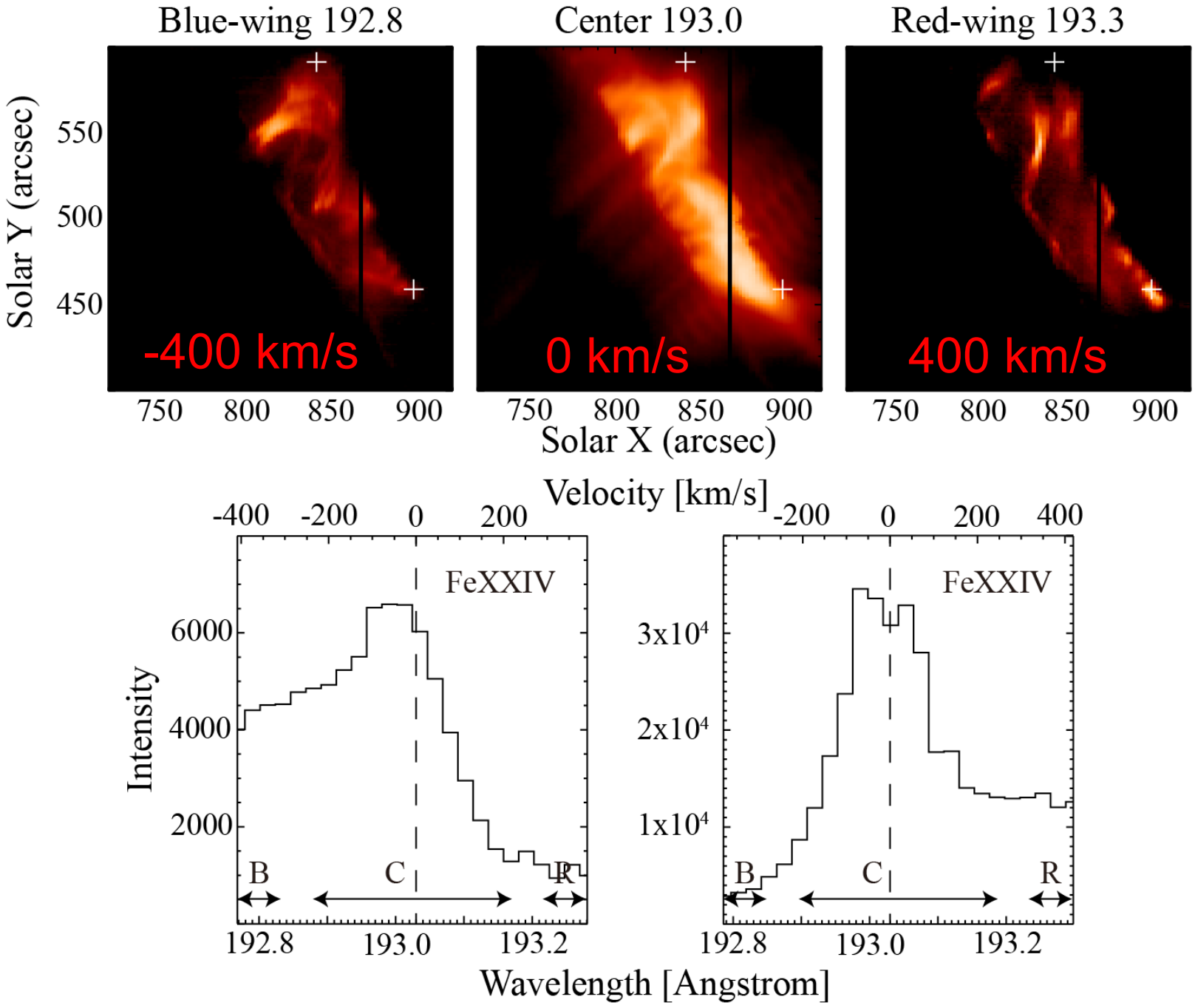
EIS observe the flare with slit scanning.

# EIS Observation



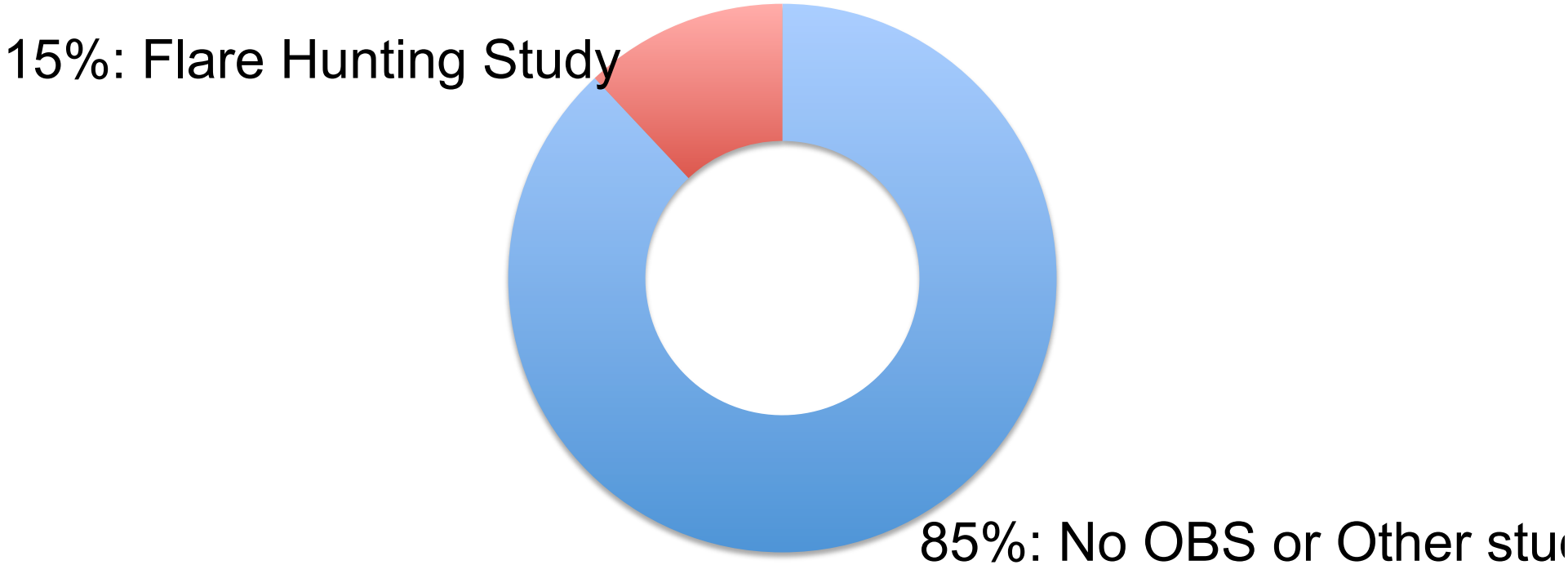

Large non-thermal broadening (>250km/s) were observed just above the flare loop.

# EIS Line Profiles



# EIS Flare Hunting Study Coverage

Survey Period ~730 days = 17520 hours
Total Flare Hunting hours = 2600 hours (15%)

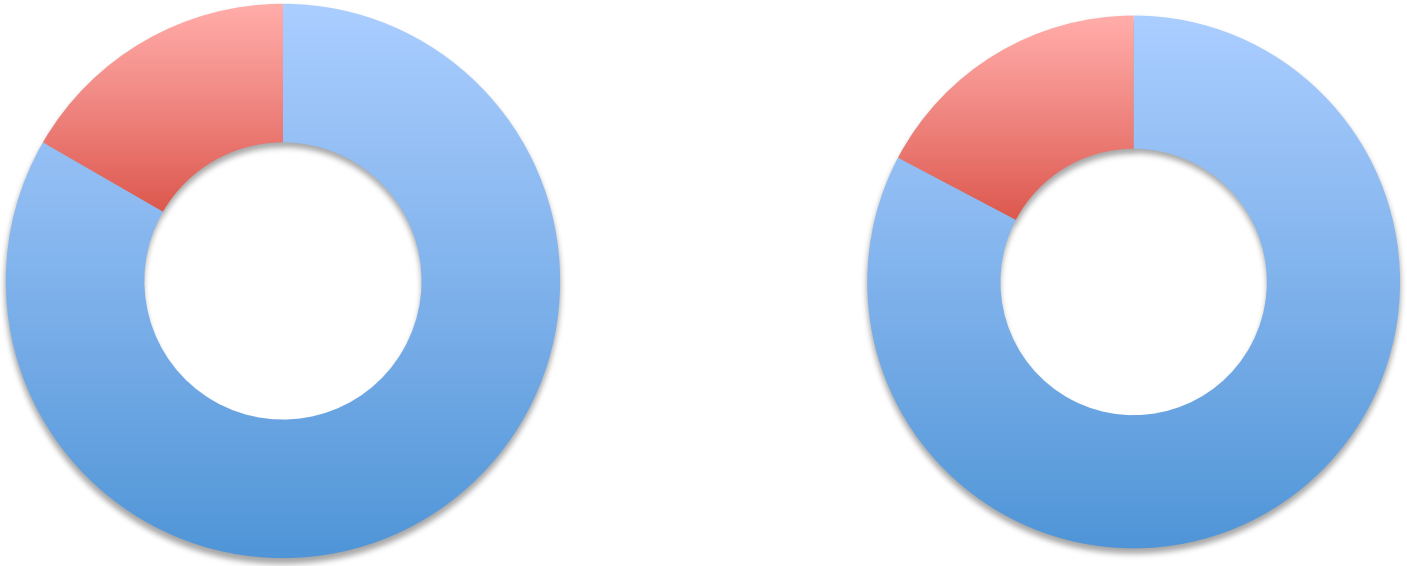


# How many flares are observed by Flare hunting study?

- 33 Major Flares (>M class) are Observed
- 2 X class are observed

Survey Period: 191 Major Flares were occurred
12 X-Class Flares were occurred

16.7%: Observed X-Class Flare17.3%: Observed Major Flare



# Capability of Flare Hunting study

Survey Period: 191 Major Flares were occurred
EIS Flare Hunt Study Observed: 33 Major Flare

## Observing Coverage

15%: Flare Hunting Study

85%: No OBS or Other study

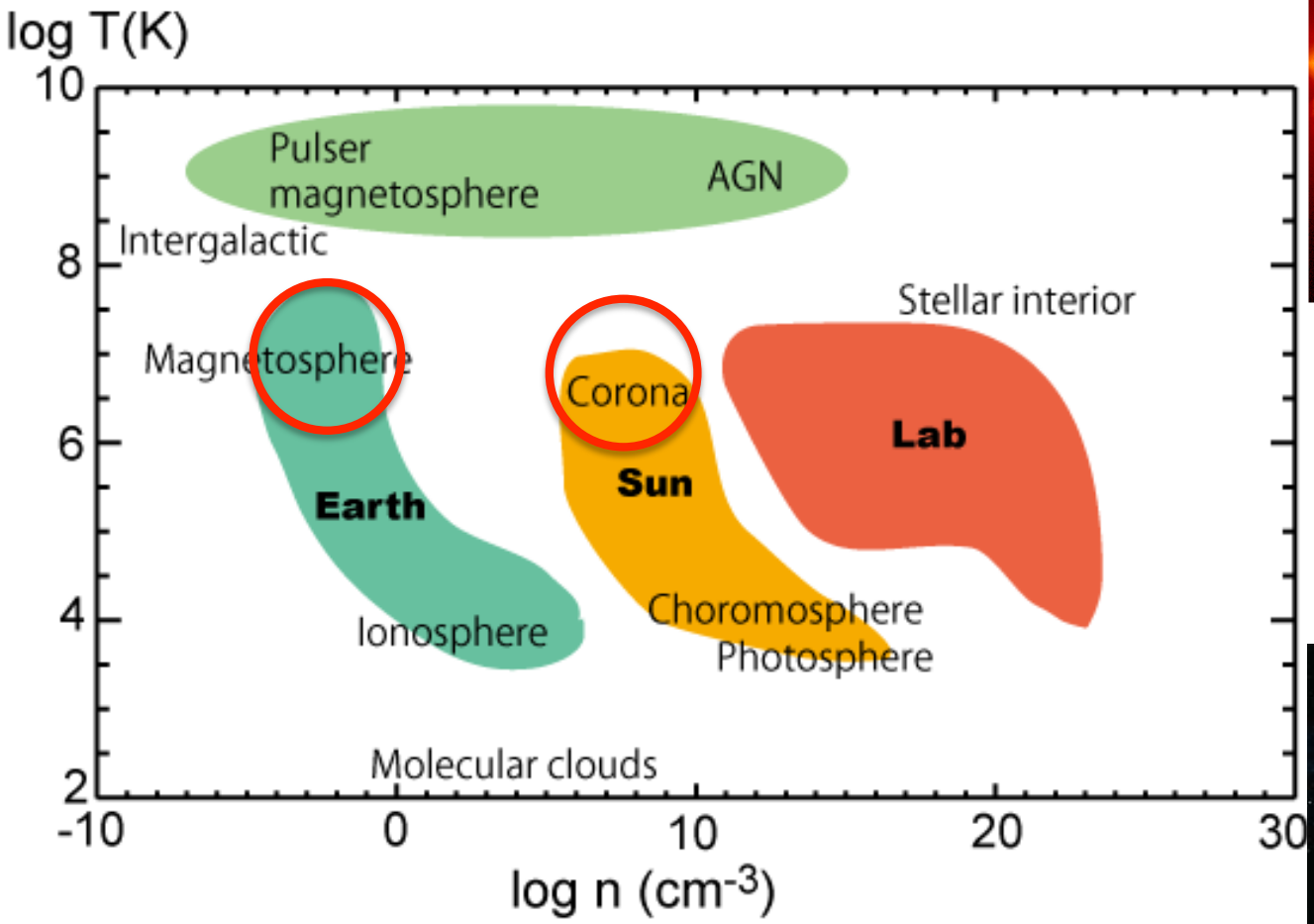
## Flare Hunting Capability

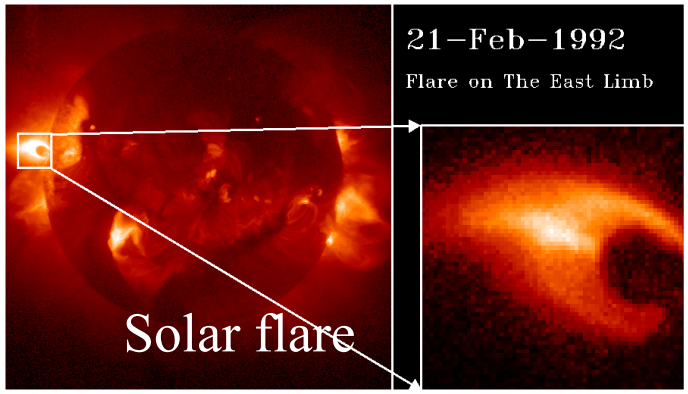
17.3%: Observed Major Flare

82.7%: Not Observed

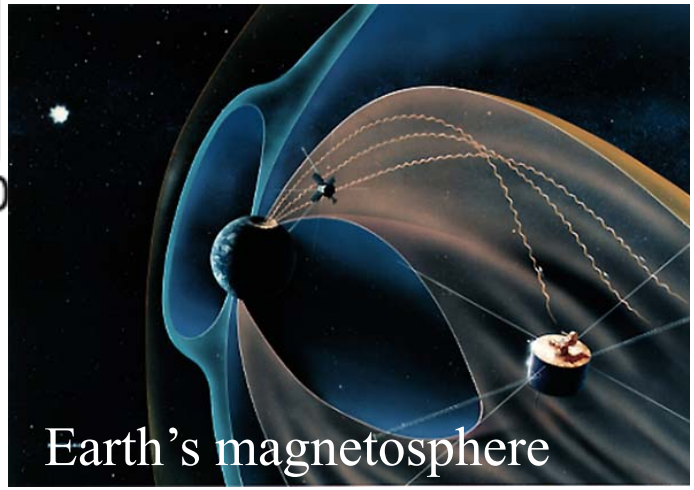
The capability is good!

# Plasmas in universe




Comparative studies important



# Solar Corona and Earth's Magnetosphere

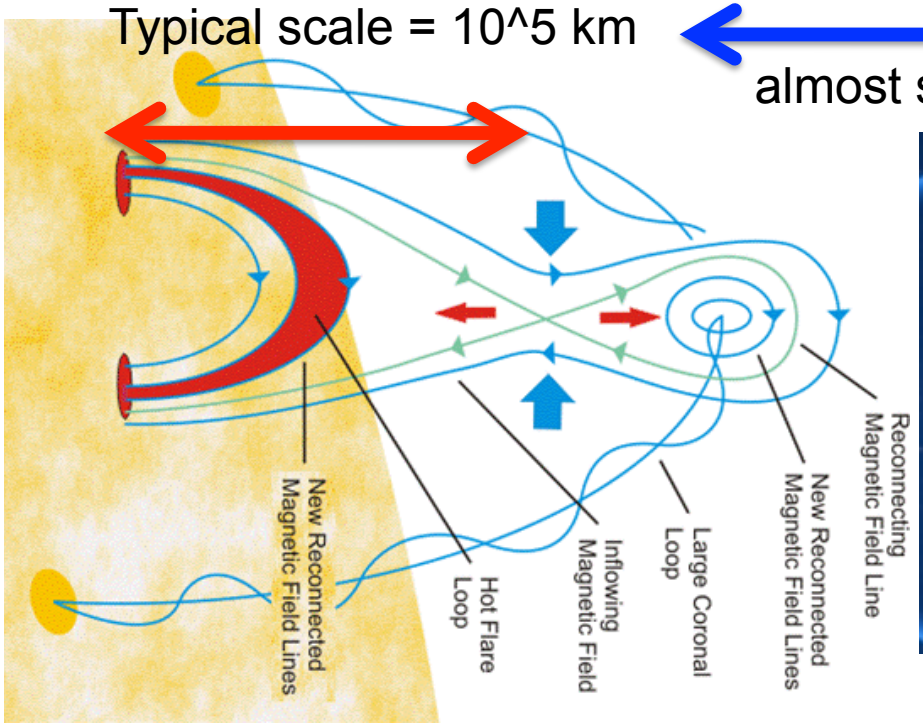
Solar corona (flare)

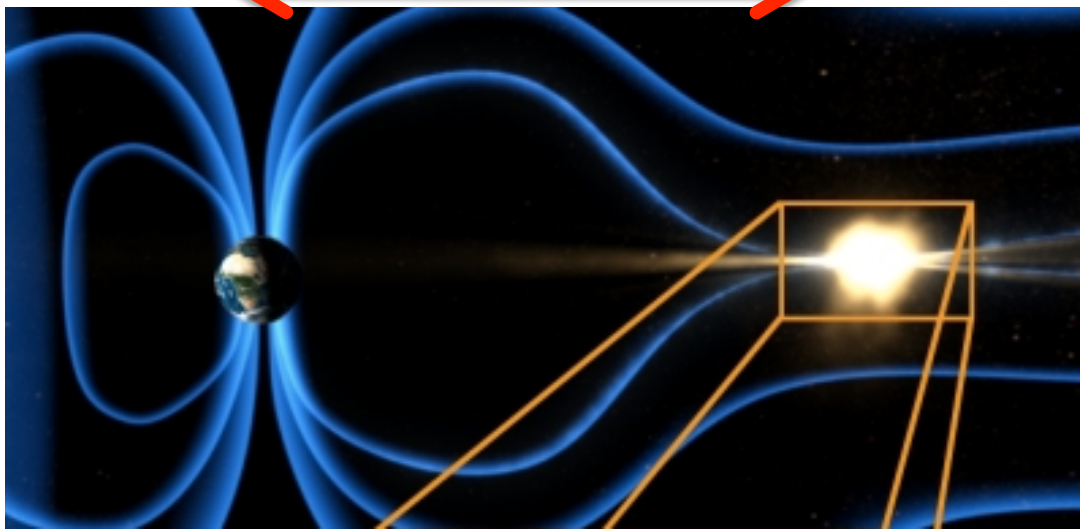
Typical scale = 10^5 km

almost same

Earth's magnetosphere (substorm)

Typical scale = 10^5 km

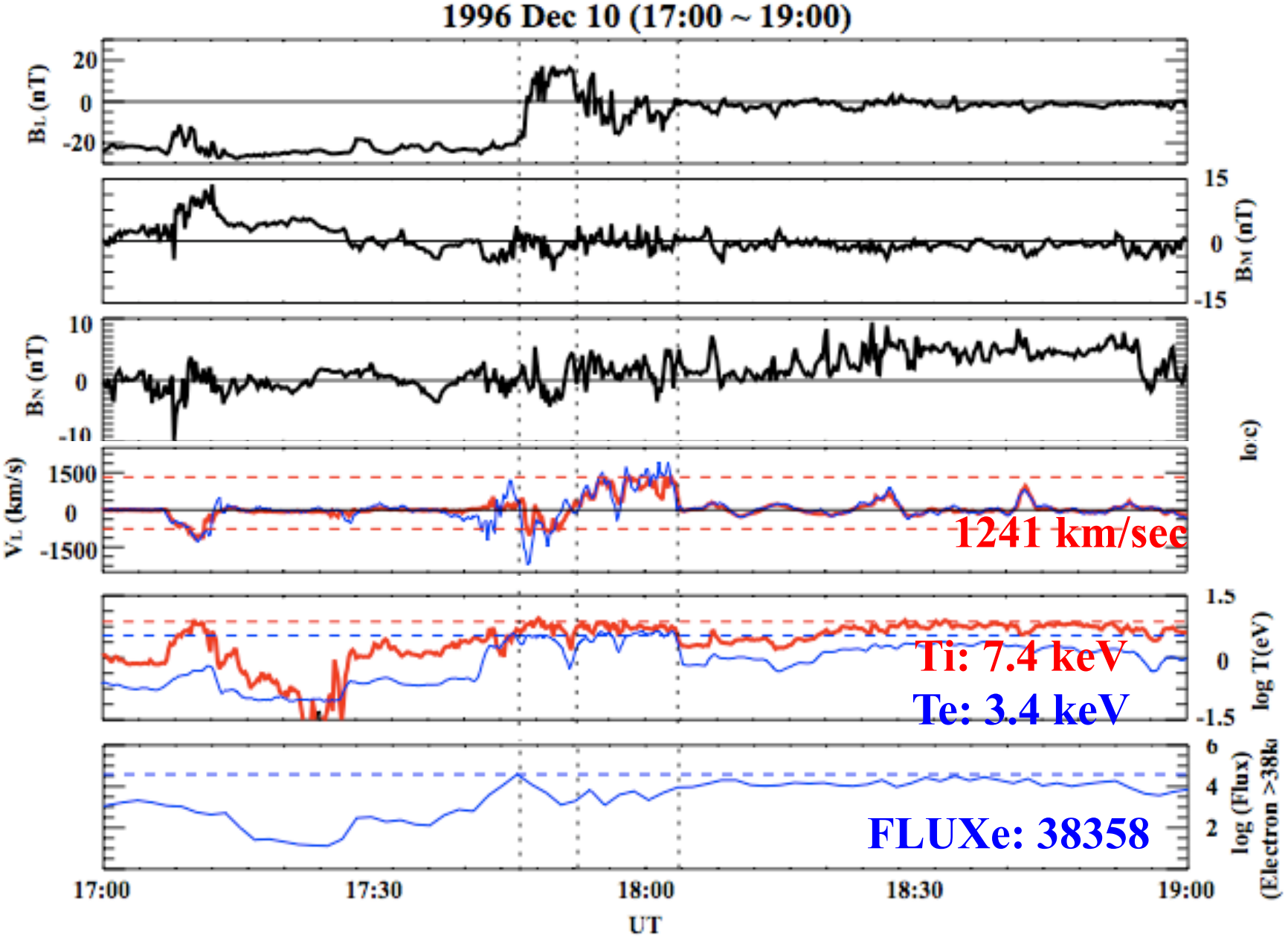


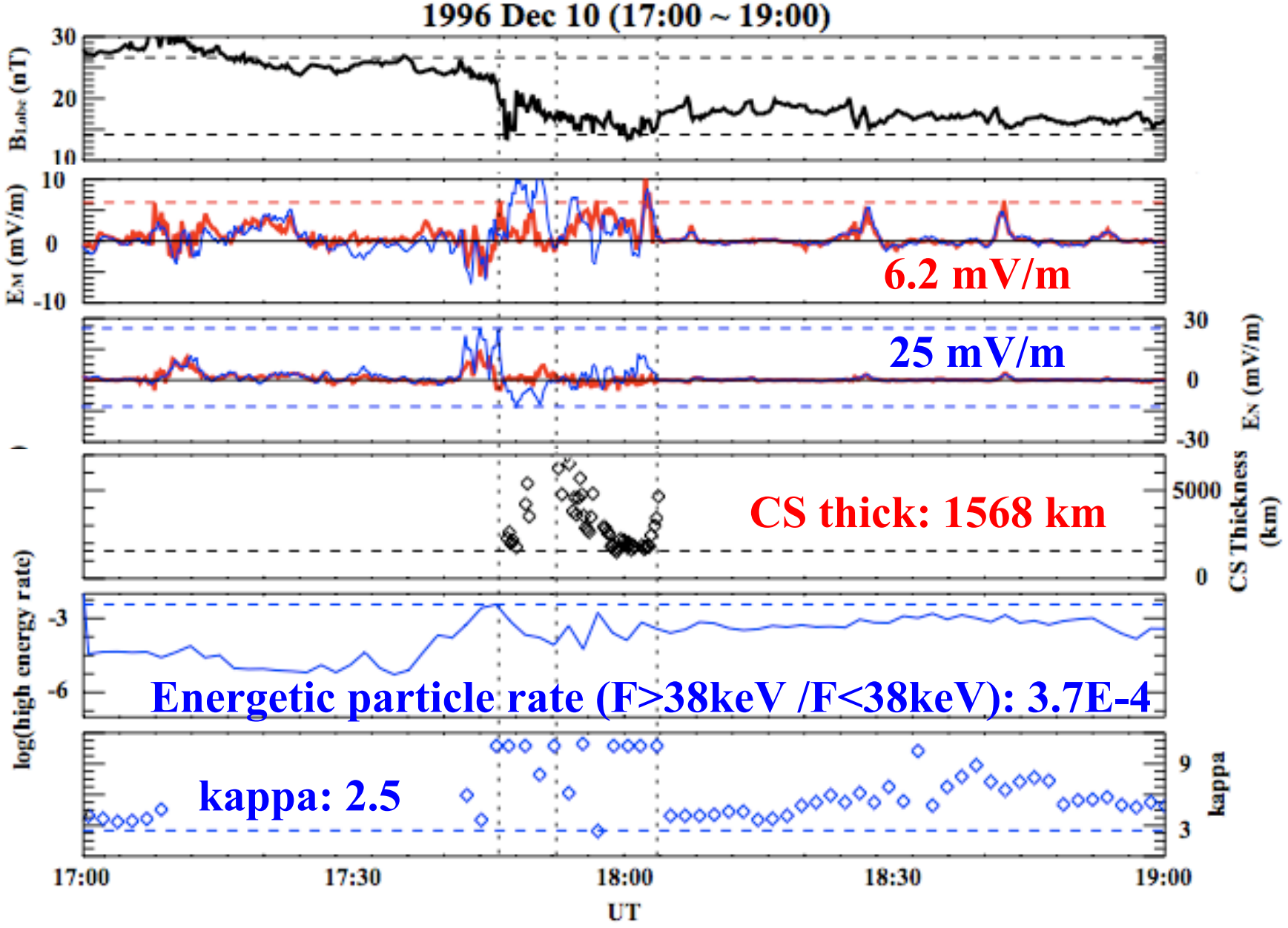
| | | | | |
|---|---|---|---|---|
| Macro-scale | → | Sun : $10^5$ km | Earth : $10^5$ km | same |
| Micro-scale | → | Sun : $10^{-3}$km | Earth : $10^3$ km | 6 order |
| Macro/Micro | → | Sun : $10^8$ | Earth : $10^2$ | 6 order |

→ Macro/Micro is largely different!

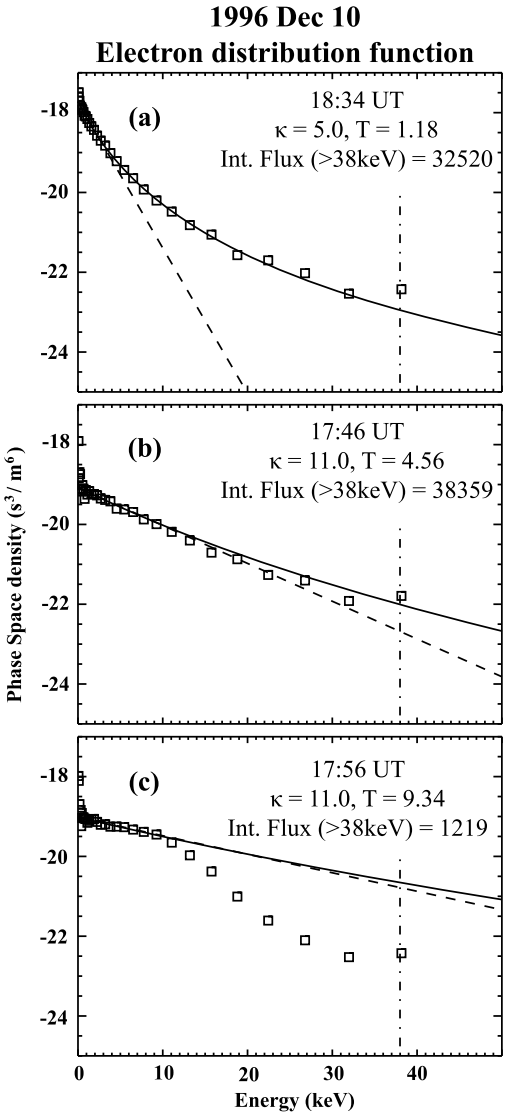
# Example of Energetic Electron acceleration by MRX in Magnetosphere



# Example of Energetic Electron acceleration by MRX in Magnetosphere

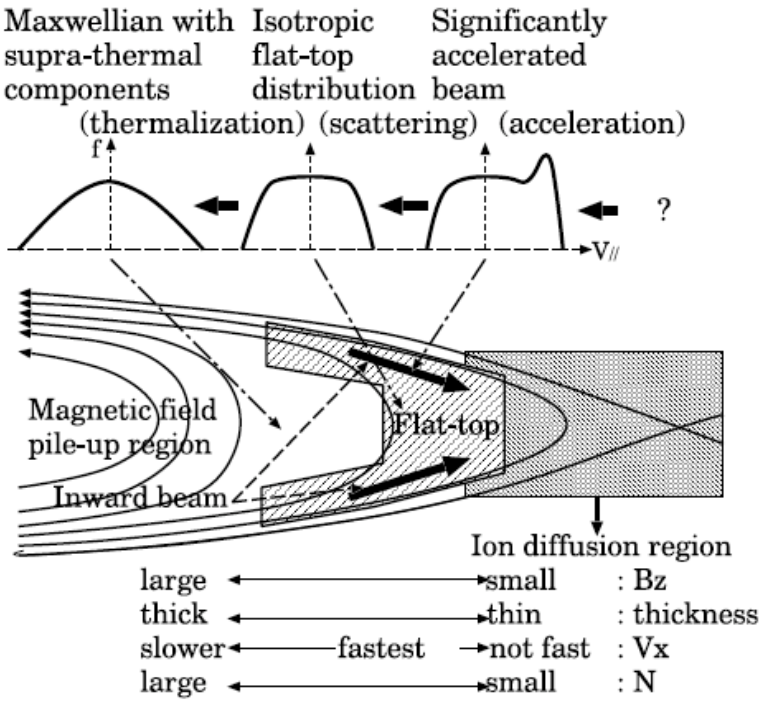


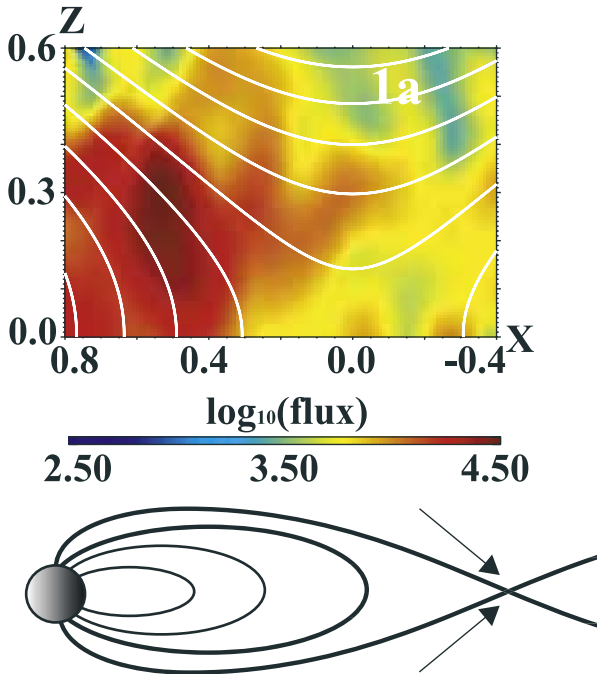
# リコネクション周辺の分布関数




Imada et al. 2011 JGR.

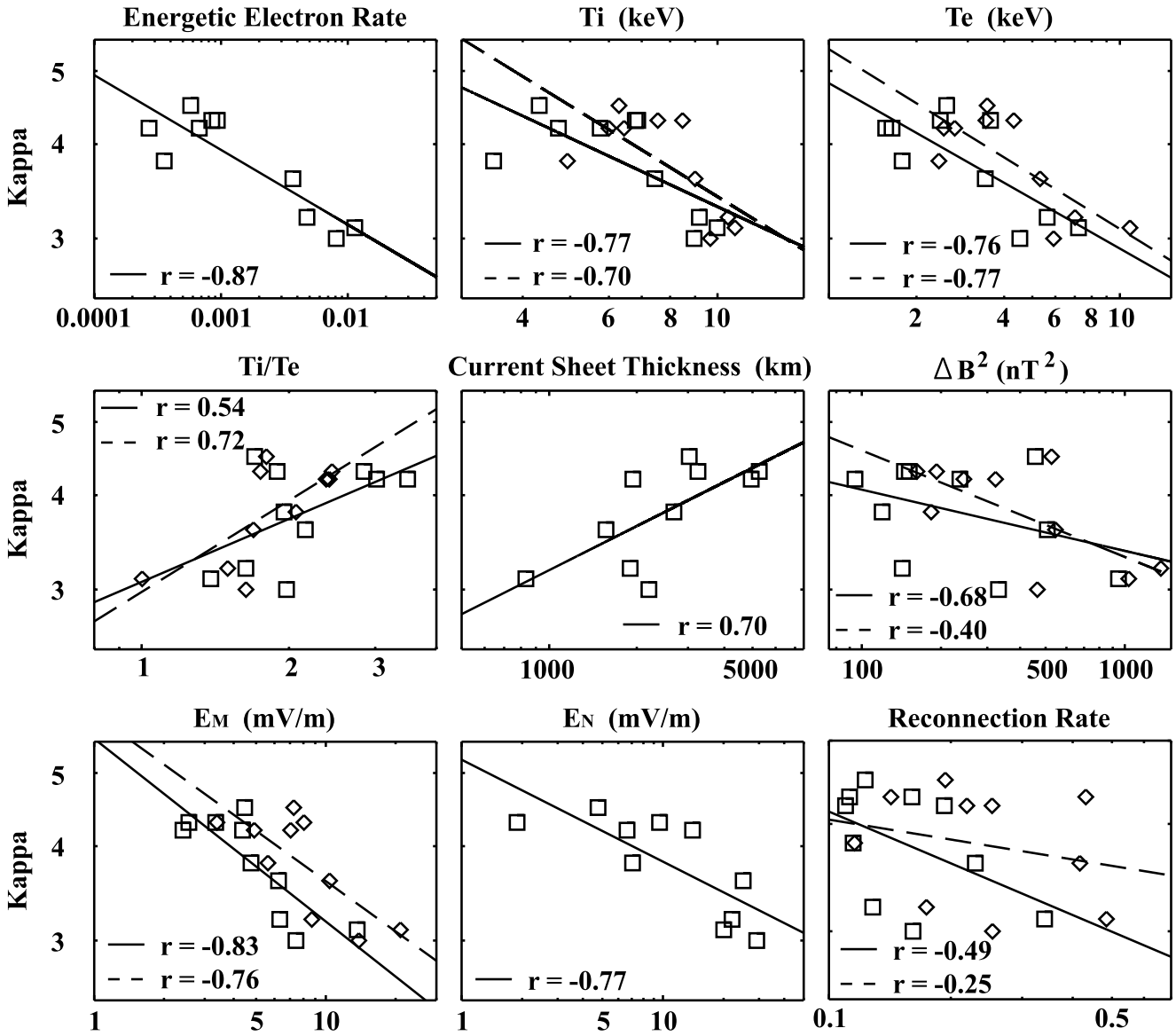
Asano et al. 2008 JGR.




Imada et al. 2005 GRL.

# Correlation between energetic electrons and other plasma parameters

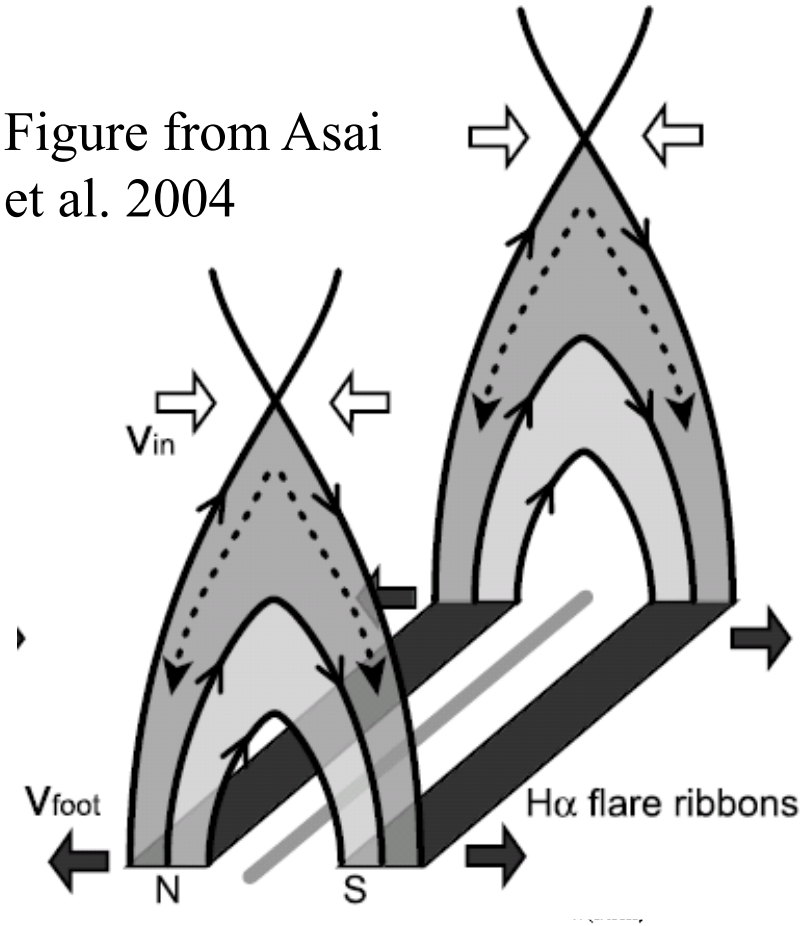


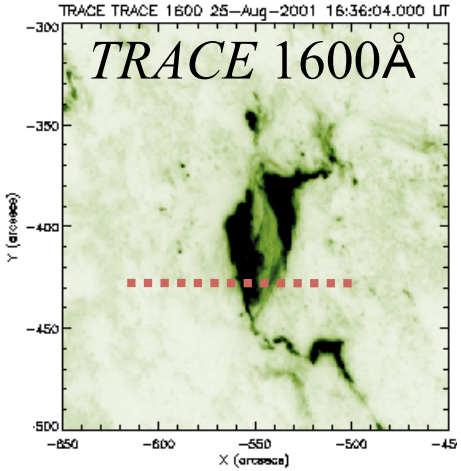

Imada et al. 2011 JGR

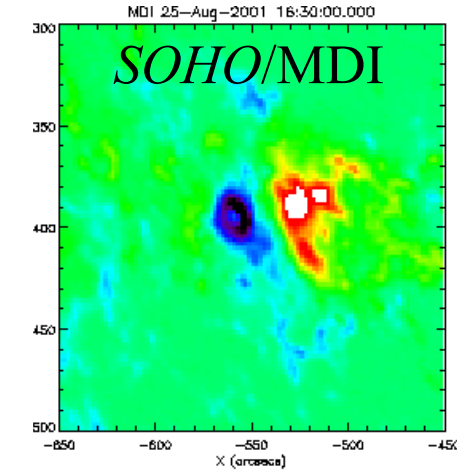
# Reconnection electric field

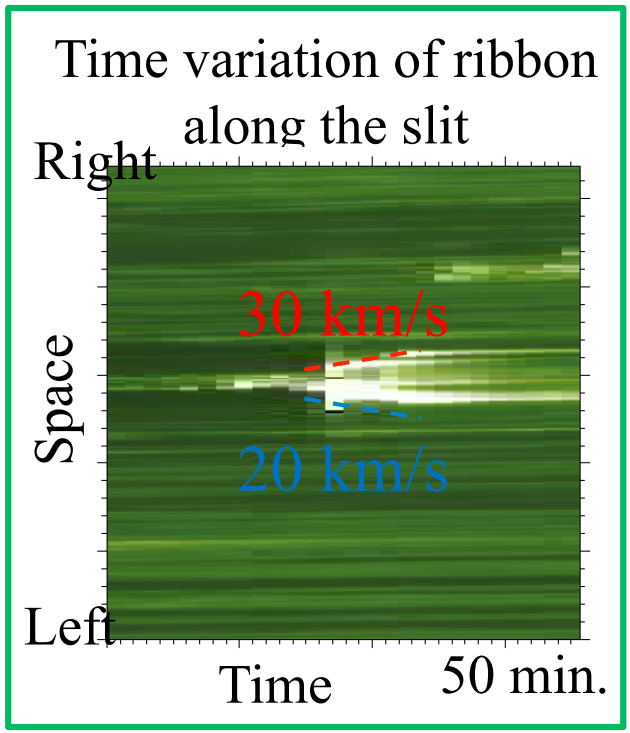
2001/08/25 flare

Figure from Asai et al. 2004




| | B [G] | L [km] |
|---|---|---|
| Right | 500 | 40,000 |
| Left | 700 | 50,000 |

Reconnection electric field:

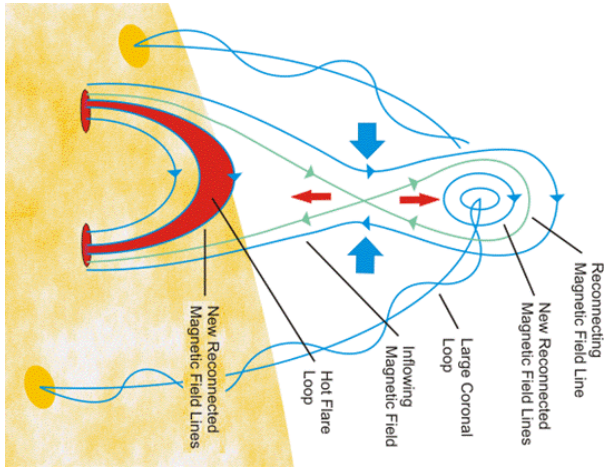
$E = V_{\text{in}} B_{\text{corona}} = V_{\text{foot}} B_{\text{photosphere}}$

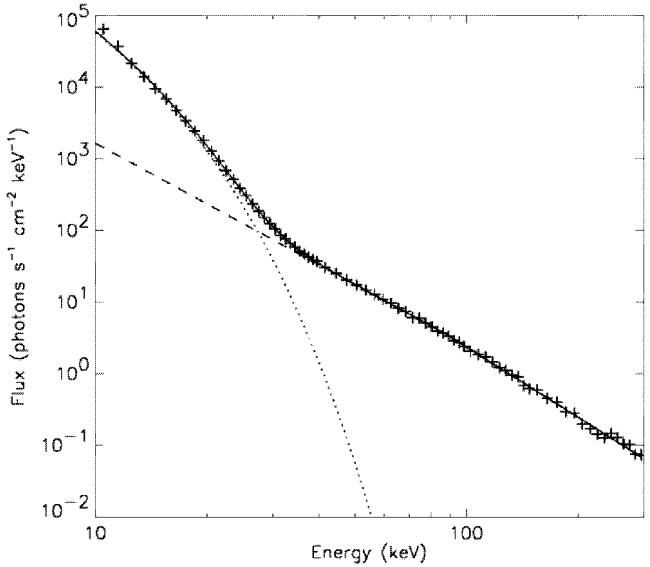
[Qiu et al. 2002, Isobe et al. 2002, Asai et al. 2004]

$$E = \frac{v_{\text{FP}} B_{\text{FP}}}{c} \sim 14 - 15[\text{V/cm}]$$

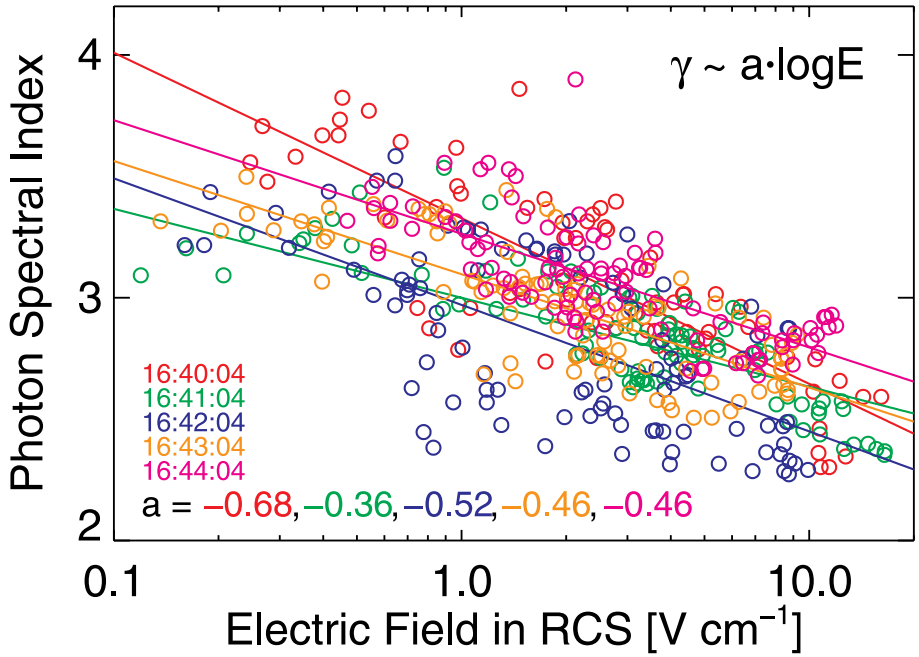
$$K_{\max} \cong eEL \sim 60 - 70[\text{GeV}]$$

# Magnetic reconnection and particle acceleration in Flare



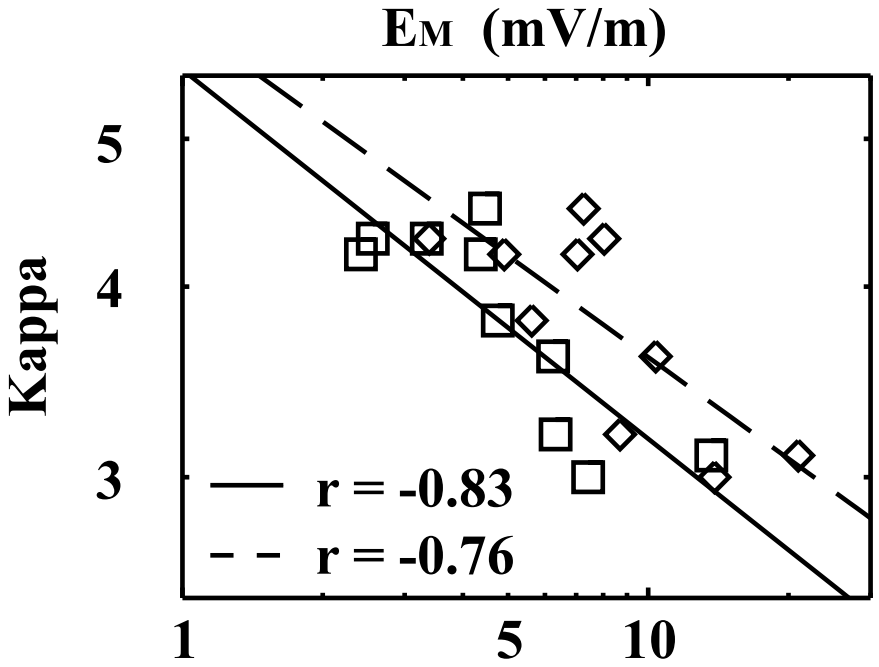

X-ray spectrum observed by RHESSI
[Lin et al., ApJ, 2003]



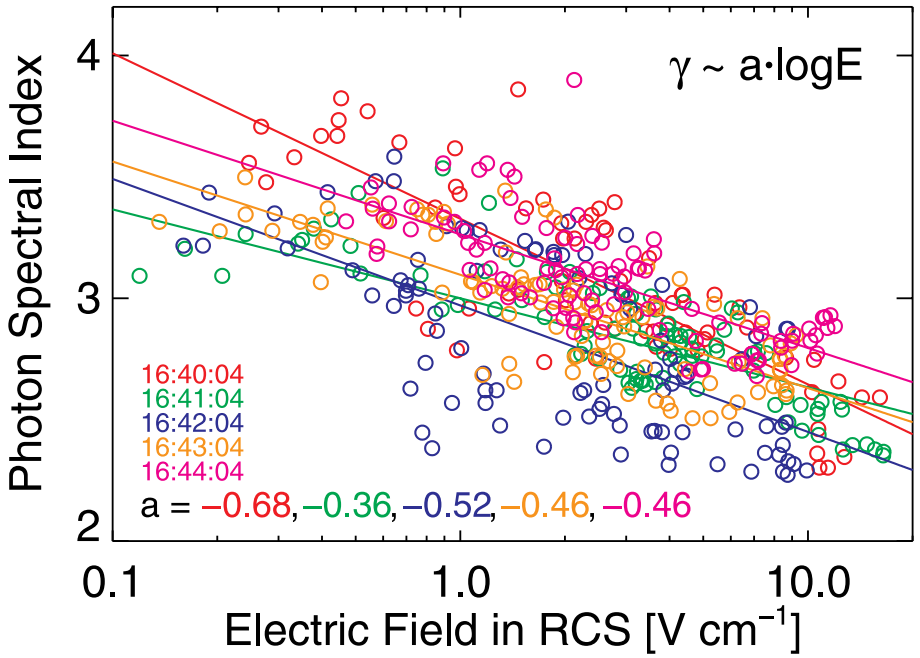

Harder electron spectrum when stronger reconnection electric field in solar flares
[Liu et al., ApJ, 2008]

# Comparison between Solar and Earth's magnetosphere

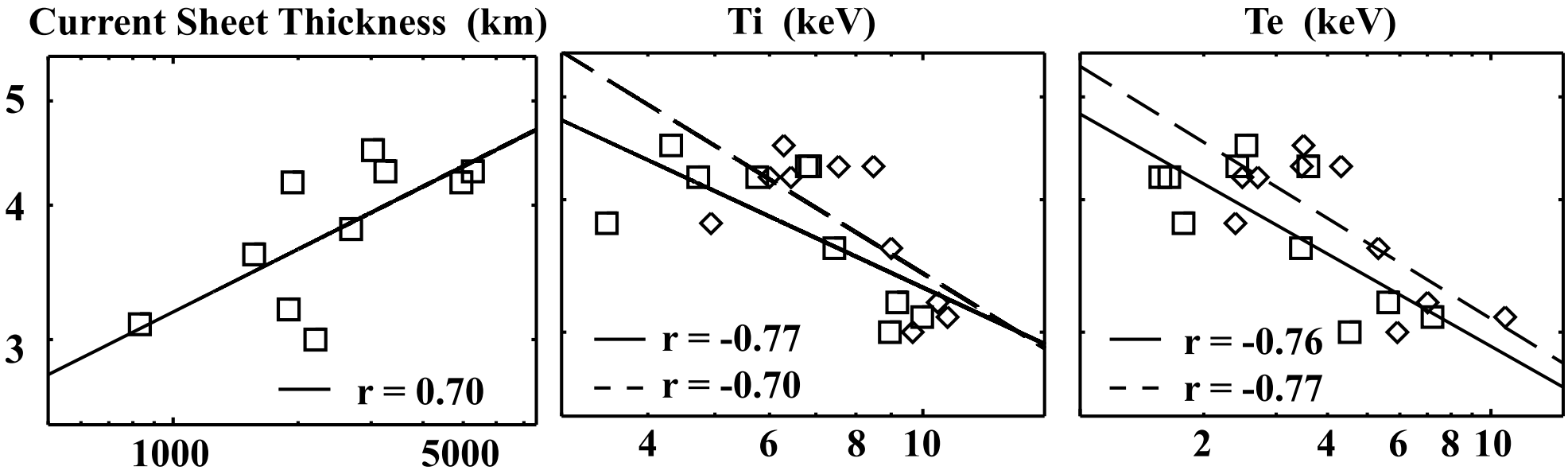
Earth's Magnetosphere




Solar Corona



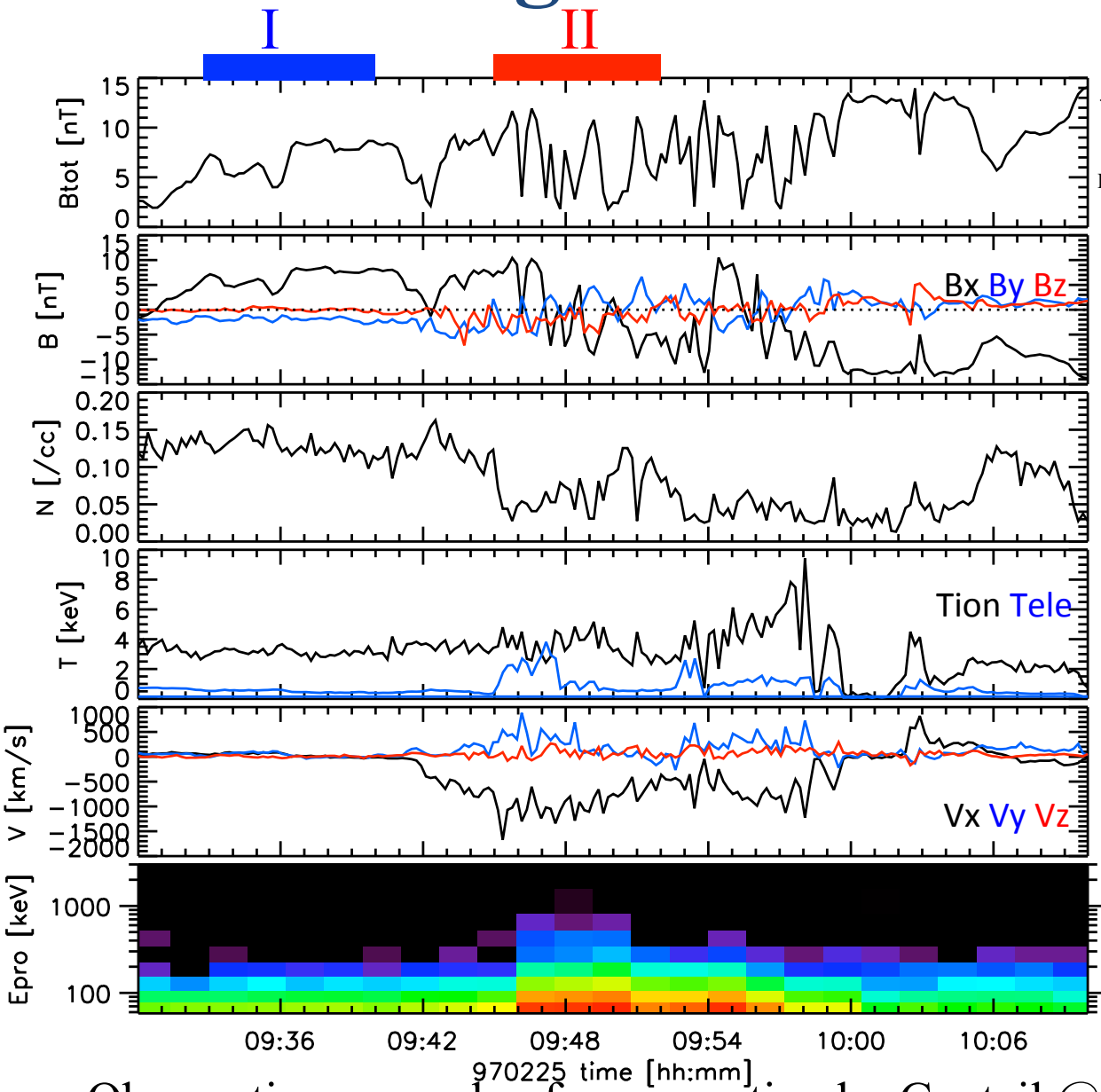

Energetic electron acceleration are well related to reconnection electric field in both of Earth's magnetosphere and Solar corona!

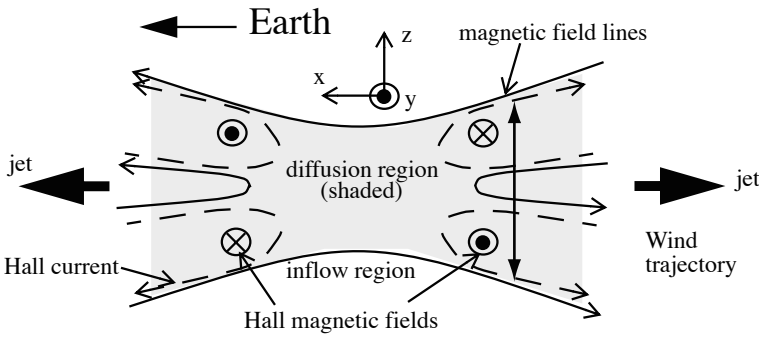



Estimate Current sheet thickness in solar corona is difficult (almost impossible…)

Determine temperature in reconnection region is also difficult… now trying with Hinode obs.

# Ion accelerated reconnection event in Earth's magnetotail



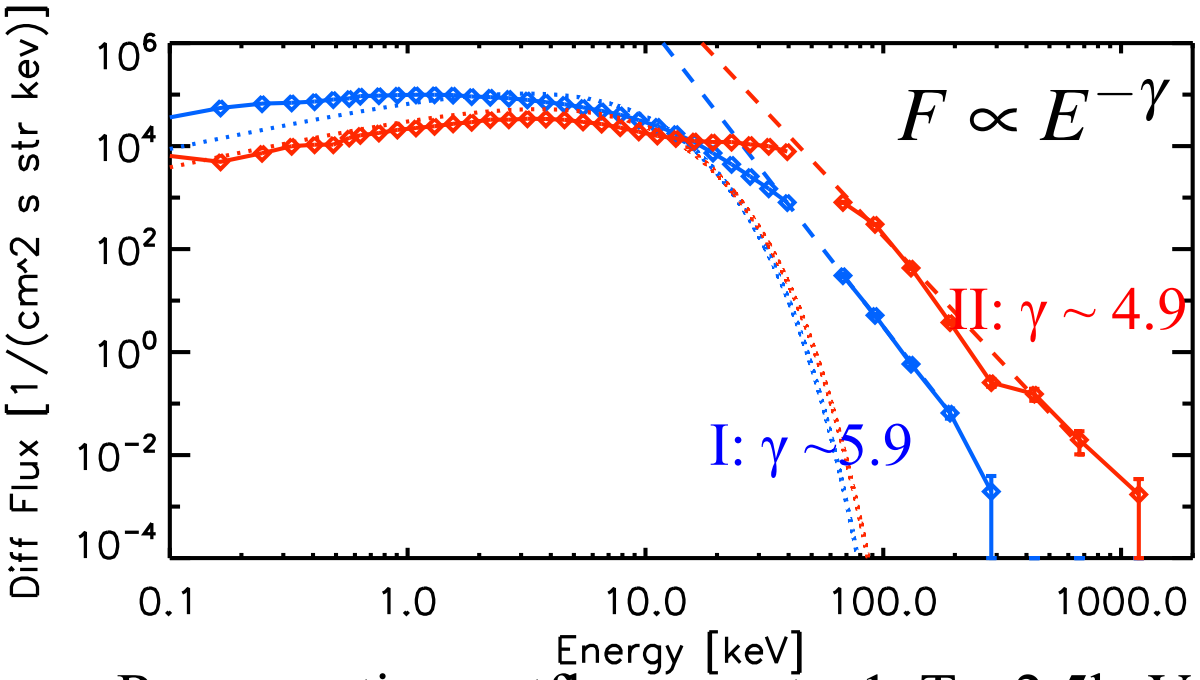




- Fast Alfvenic flow
- Weak magnetic field
- strong ion/electron heating
- Hall magnetic field

**Hirai et al. in prep.**

Observation example of reconnection by Geotail @$(X, Y, Z)_{GSM}$ = (-27, 6, -1) $R_E$

# Observation of energetic ions in Earth's magnetotail




Energy spectrum of protons observed by Geotail spacecraft (LEP+EPIC) in the Earth's magnetotail

I: Before the onset

→ II: After

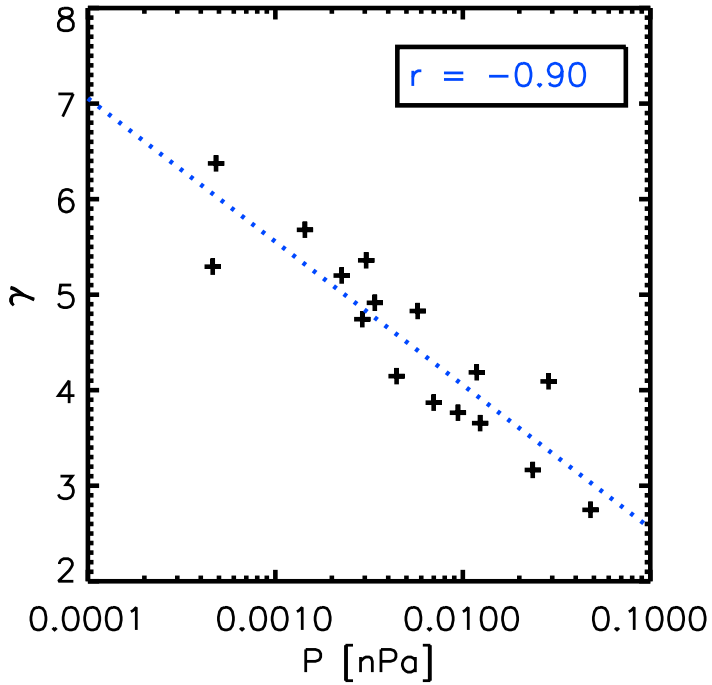
Reconnection outflow events: 1. Te>2.5keV and 2. V>1000km/s

Ion accelerated events: significant increase of energetic proton flux above the background level

(Maximum potential drop in magnetosphere ~ a few hundred keV)

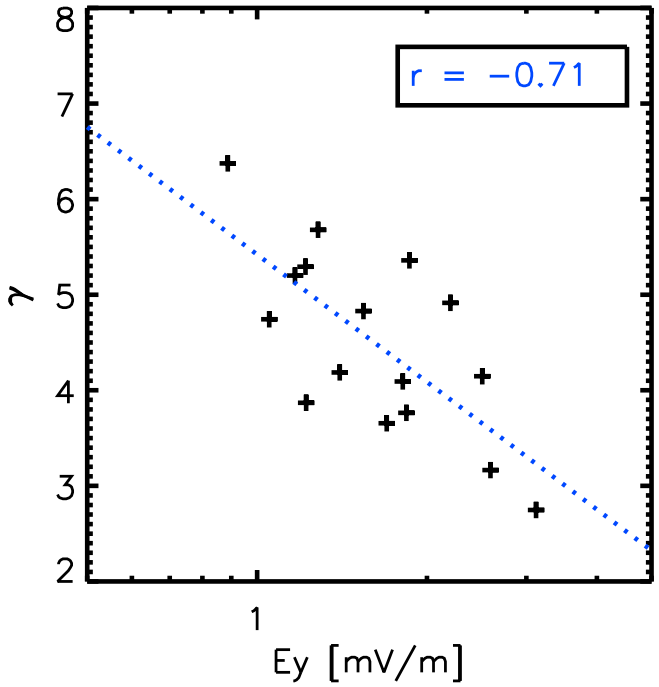
→ Statistical study based on 16 ion accelerated reconnection events observed by Geotail in 1993-1999.

# Ion acceleration and reconnection electric field in Earth's magnetotail




energy density of accelerated ions (>100keV)

spectral index



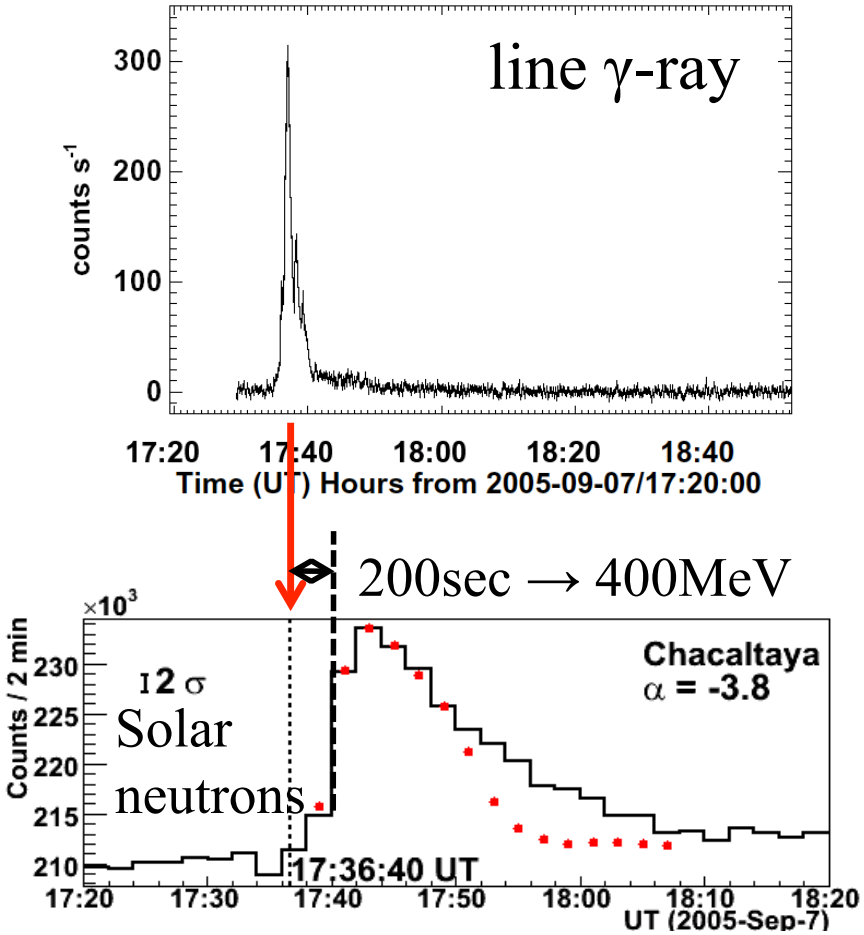

reconnection electric field

Efficient ion acceleration when larger reconnection electric field.
(Hard spectrum index and large energy density of energetic ions)

# Ion accelerated events in Solar corona: Estimation of maximum energy

Estimated the maximum energy and spectral index of accelerated ions from time-of-flight method and Mote-Carlo simulation.

| Date | max. energy [GeV] | Spectral index |
|---|---|---|
| 2000/11/24 | 0.7 | 5.2 |
| 2001/08/25 | 0.6 | 4.0 |
| 2003/10/28 | 1.4 | 4.8 |



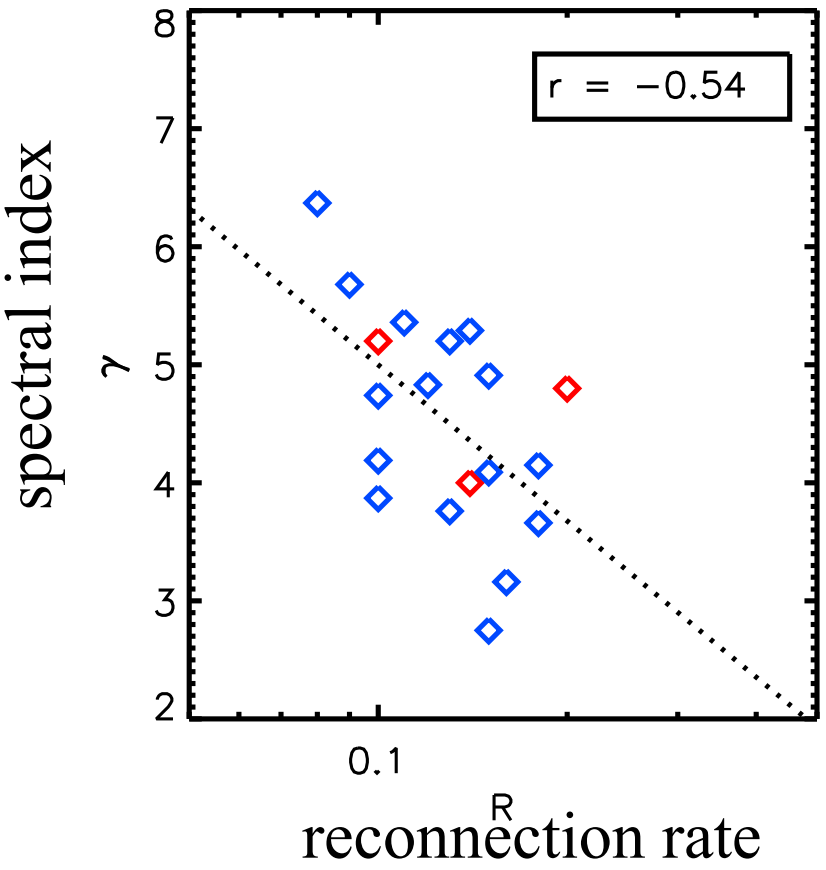

Watanabe et al., ASR, 2009

# Ion acceleration and reconnection electric field in Solar corona

| | Observed max. energy [GeV] | spectral index | total proton counts | neutron total energy [erg/sr] | Estimated electric field [V/cm] | Estimated max. energy [GeV] |
|---|---|---|---|---|---|---|
| 2000.11.24 | 0.7 | 5.2 | $7.0\times10^{31}$ | $1.8\times10^{25}$ | 10 | 50 |
| 2001.8.25 | 0.6 | 4.0 | $3.3\times10^{31}$ | $9.0\times10^{24}$ | 14-15 | 60-70 |
| 2003.10.28 | 1.4 | 4.8 | $6.0\times10^{32}$ | $1.6\times10^{26}$ | 20-70 | 200-420 |

✧ Large electric field and potential in the 2003/10/28 event which has large maximum energy as well as large accelerated ion flux.
✧ Accelerated ions have obtained only ~1% of the potential energy.

# Comparative study: Ion acceleration and reconnection rate

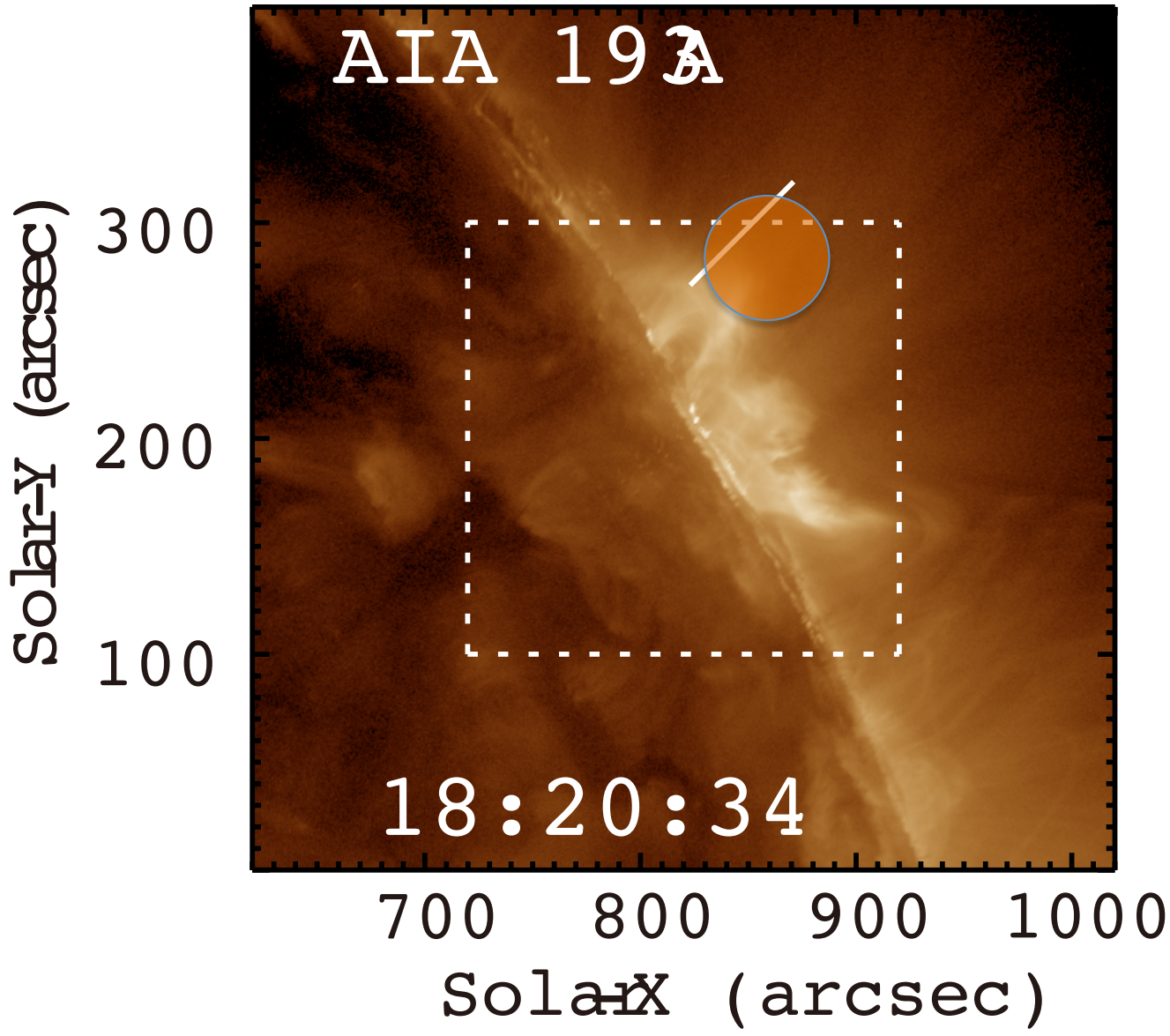


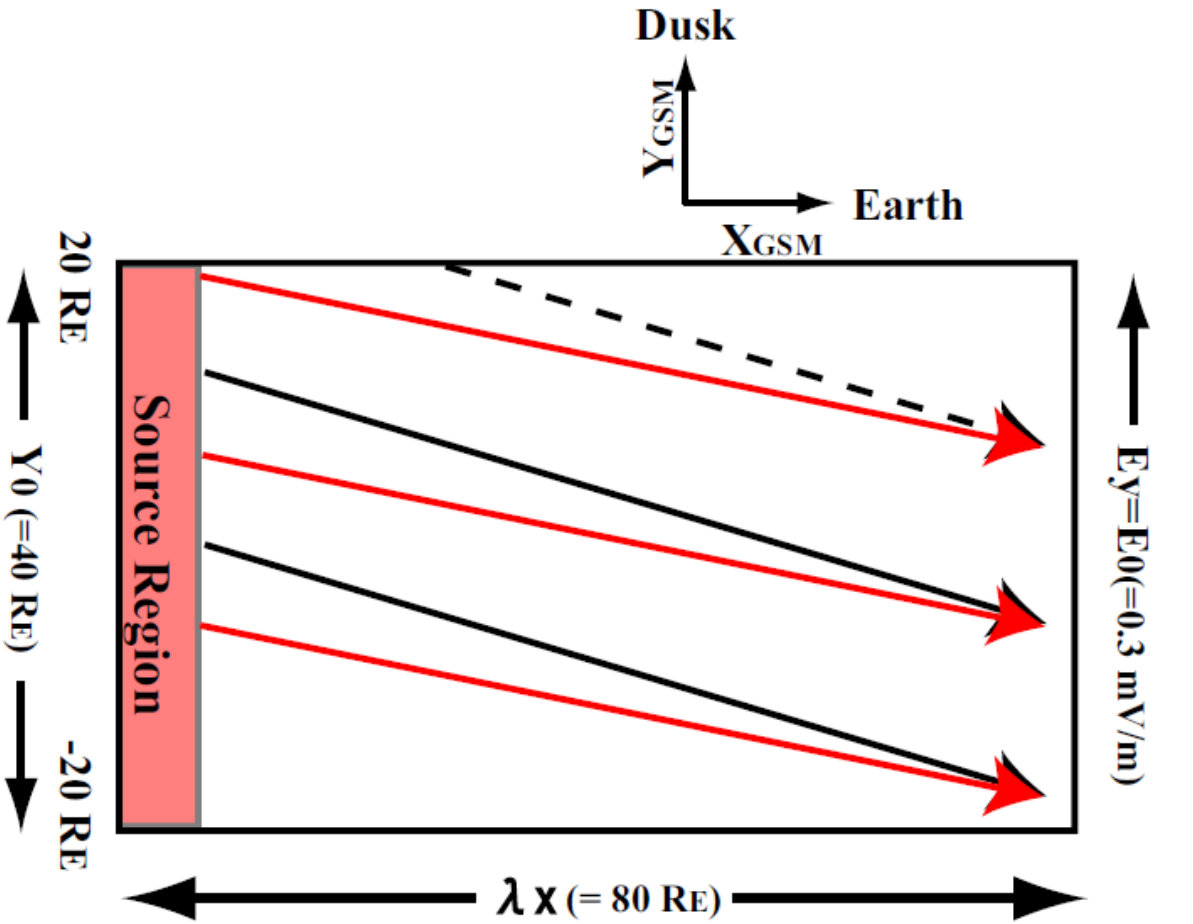

◇ Solar corona

◇ Earth's magnetotail

| Physical quantity | Solar corona | Earth's magnetotail |
|---|---|---|
| E [V/cm] | 10 | $10^{-5}$ |
| B [G] | $10^{2}$ | $10^{-4}$ |
| $V_A$ [cm/s] | $10^{8}$ | $10^{8}$ |
| E/B | $3\times10^{-4}$ | $3\times10^{-4}$ |
| R | 0.1 | 0.1 |

Particle acceleration rate is heavily depend on Reconnection rate.
Maximum energy / Potential drop is quite different between Sun and Earth.
Corona ~ 1%, Magnetosphere > 100%

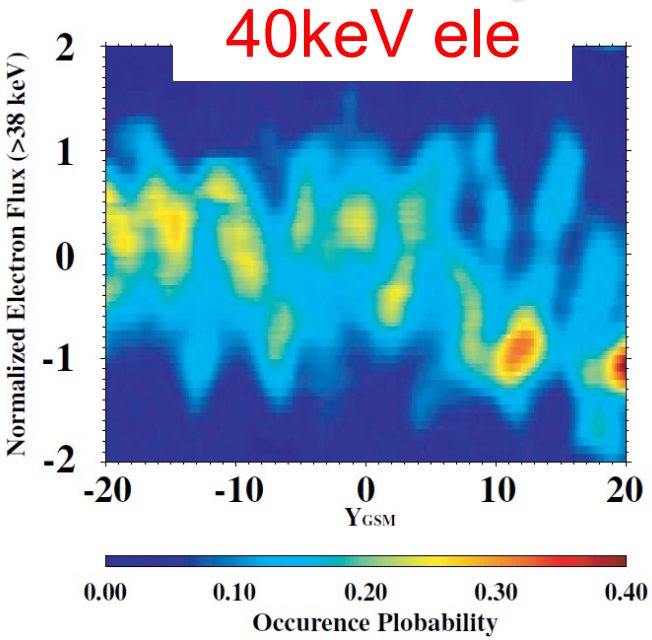

AIA 193 Å
18:20:34
300
200
100
Solar-Y (arcsec)
700
800
900
1000
Solar-X (arcsec)

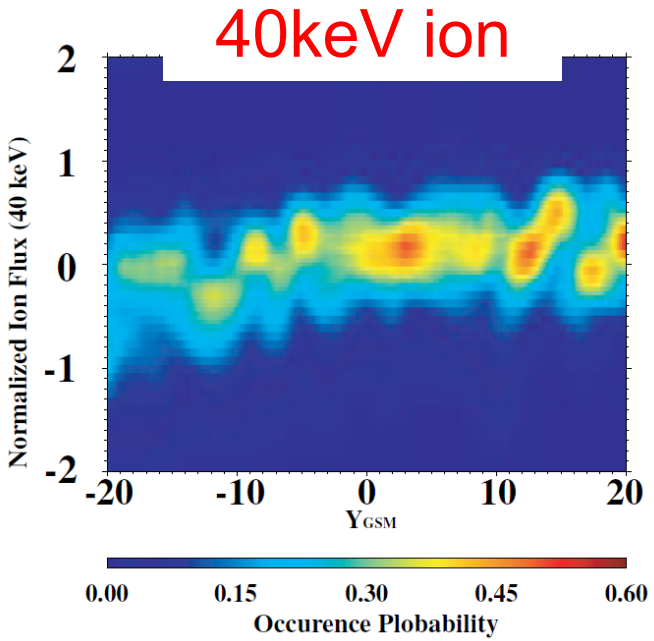


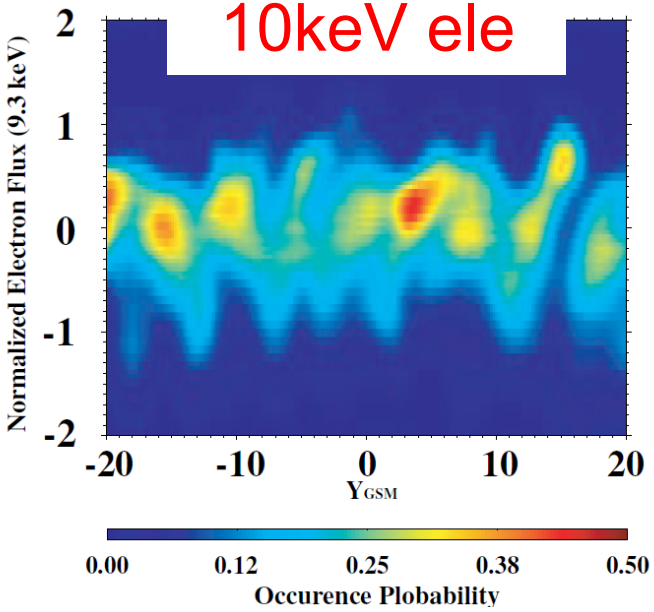

$$Bz = B0\,[\,(\alpha - 1)\,(X + 20 + \lambda x) / \lambda x + 1\,]$$

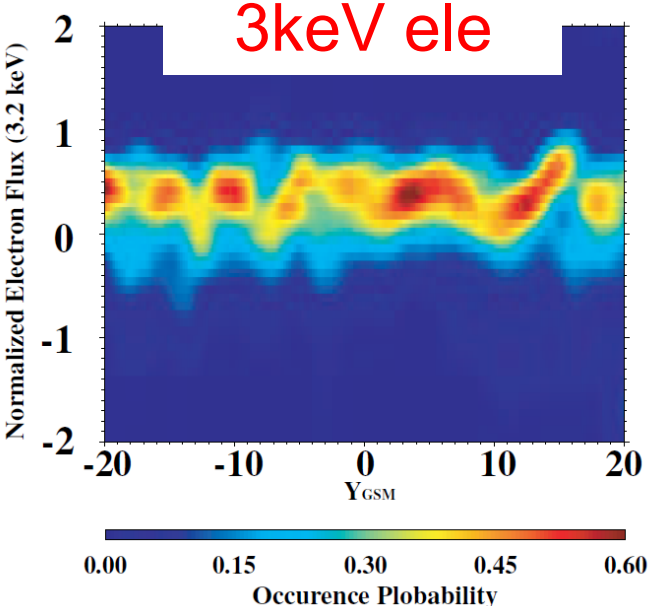
# GEOTAIL: Dawn-Dusk Asymmetry

Electric field



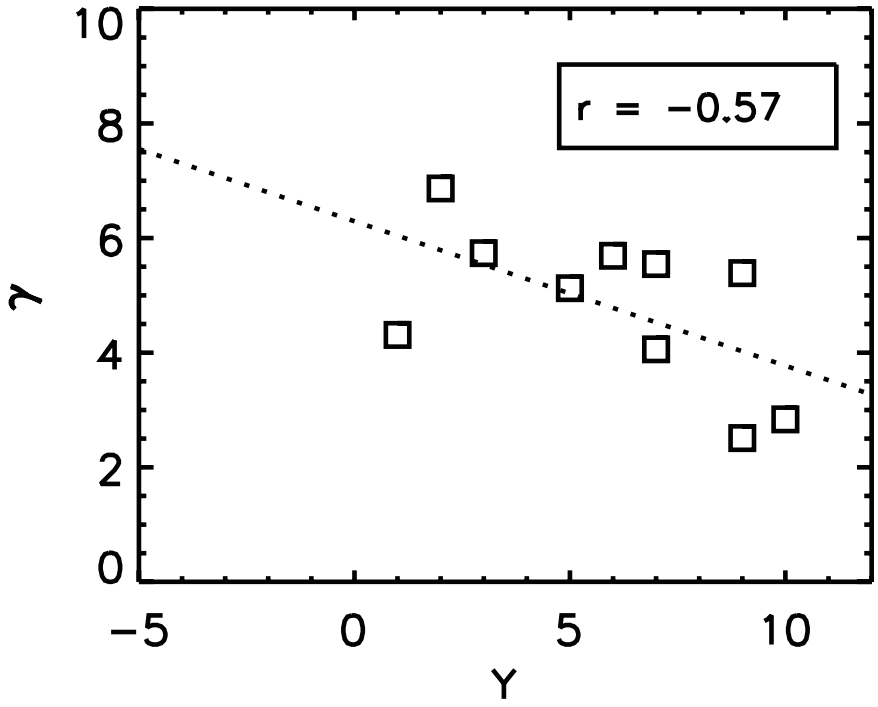



# Dawn-Dusk asymmetry

MeV Ion




40 keV electron